Abstract

This thesis reports results of MCNP-5 calculations, with the nuclear data library FENDL-2.1, to assess the effect on the Tritium Breeding Ratio (TBR) when integrating a distributed Ion Cyclotron Range of Frequencies (ICRF) antenna in the blanket of a DEMO fusion power reactor. Apart from a representative final configuration of both the antenna and the DEMO reactor, a parametric analysis is done on the parameters which most strongly affect the TBR. These are the type of breeding blanket (Helium Cooled Pebble Bed, Helium Cooled Lithium Lead and Water Cooled Lithium Lead), the covering ratio of the straps of the antenna (0.49, 0.72 and 0.94), the depth of the antenna (20 cm and 40 cm), the thickness of the straps (2 cm, 4 cm and a double layer of 0.2 cm plus 2.5 cm with the composition of the First Wall), and finally the poloidal position of the antenna (0º, which is the equatorial port, 40º and 90º, which is the upper port).

For an antenna with a full toroidal circumference of 360º, located poloidally at 40º with a poloidal extension of 1 m and a total First Wall surface of 67 m^2, the reduction of the TBR is 0.35% for a HCPB blanket concept, 0.53% for a HCLL blanket concept and 0.51% for a WCLL blanket concept.

In all cases, including the parametric analysis, the loss of TBR remains below 0.61%, and the antenna is thus shown to have only a marginal effect on the TBR for a DEMO reactor.

ETSEIB

Vull dedicar aquest projecte a la memòria del meu company i amic Antoni Barceló. Diuen que un no mor fins que és oblidat, i penso que la millor manera de no fer-ho és portant dins meu una petita part teva i compartir-hi tota experiència que sé que t'hagués agradat viure.

Així doncs, i com a company d'universitat que vas ser, comparteixo amb tu aquest final d'etapa i amb un somriure et dic que no, no t'he oblidat.

Aquesta és la meva polsera vermella.

Summary

1. Glossary

AHM	Auxiliary Heating Method
COBS	Central Outboard Blanket Segment
DEMO	DEMOnstration power plant
ECRH	Electron Cyclotron Resonance Heating
EFDA	European Fusion Development Agreement
F4E	Fusion for Energy
FW	First Wall
HCLL	Helium Cooled Lithium Lead
HCPB	Helium Cooled Pebble Bed
ICRF	Ion Cyclotron Range of Frequencies
IFMIF	International Fusion Materials Facility
ITER	International Thermonuclear Experimental Reactor
LIBS	Left Inboard Blanket Segment
LOBS	Left Outboard Blanket Segment
MMS	Multi Module Segment
NB	Neutral Beam
PPPT	Power Plant Physics and Technology
RIBS	Right Inboard Blanket Segment
ROBS	Right Outboard Blanket Segment
TBR	Tritium Breeding Ratio

Tokamak	*TOroidalnya KAmera ee MAgnetnava Katushka*
VV	Vacuum Vessel
WCLL	Water Cooled Lithium Lead

2. Preface

The necessity of this work appears at the same time than the Ion Cyclotron Range of Frequencies (ICRF) distributed antenna starts being studied. As soon as any new device or improvement is done for DEMOnstration Power Plant (DEMO), the next step in Nuclear Fusion roadmap after ITER (International Termonuclear Experimental Reactor), it must fit the previous requirements and boundary conditions settled.

The major neutronics requirement for DEMO is to be self-sufficient in tritium. Even if the IRCF distributed antenna is suitable in heating terms, it will not be implemented if it does not ensure this previous requirement. Then, a device integrated in-blanket which uses 67 m^2 of First Wall throughout the whole 360° of the tokamak may seem rather unfeasible in tritium self-sufficiency terms, so it is one of the first questions needed to be answered in order to keep studying its heating properties.

My nuclear education was fully focused on nuclear fission, so doing my Final Degree Project in another field such as nuclear fusion was a big challenge for me. When I was suggested this topic I realized it was a neutronics project and therefore I could apply my fission knowledge while learning a new field. Furthermore, the fact this project is for DEMO and not for ITER adds a challenging component, because most of the parameters for it are not yet fully defined.

Hence, and this is the part that I have enjoyed the most from all the experience, I have had to work in constant feedback with many experts from different fields, as well as I have had to work in different places. From Barcelona, where I did my degree, I was supposed to move to Ghent, Belgium. However, in the Max Planck Institut für Plasmaphysik (IPP) in Garching, Germany, there is a working group developing the antenna. My supervisor works in both Ghent and Garching, so I moved to Garching instead of Ghent.

After three months there, gathering all the boundary conditions for both the antenna and DEMO, I moved to the Karlsruhe Institute of Technology (KIT) in Karlsruhe, Germany, to perform neutronics simulations for five months. Meanwhile, I had the opportunity to go to Lake Arrowhead, California, to present a poster of this project into the 21st Topical Conference on Radiofrequency Power in Plasmas.

With the results of this project, including the parametric analysis done for different parameters of interest, I wanted to bring a solid reference regarding the Tritium Breeding Ratio (TBR) to people working in the antenna. The parametric analysis will help to estimate the change on the loss of TBR if any parameter is biased, which considering the long term roadmap of DEMO will likely happen.

3. Introduction

In November 2012 the European Fusion Development Agreement (EFDA) estimated the production of net fusion electricity for the grid in the early 2040 [EFDA, 2012]. This will not be achieved by ITER, which is currently being constructed and where many different technologies will be tested, but it is expected to be achieved by DEMO, the next step in the fusion roadmap. DEMO is thus a long term objective and it is still in a preliminary phase, which means that many aspects are in development.

The fuel for DEMO is deuterium and tritium. The first one can be found in nature with an isotopic abundance of 0.015% (in sea water) but the second one is radioactive and therefore needs to be produced. It can be done due to reaction shown in (3.1). It is already decided that DEMO will breed its own tritium by adding lithium in the blanket and it must be self-sufficient in tritium. The main reaction in the plasma is (3.2), and one can directly see that in reaction (3.1) a neutron is consumed and a tritium produced while in reaction (3.2) it happens in the other way. Consequently the parameter of interest for the tritium self-sufficiency is the Tritium Breeding Ratio, defined in equation (3.3), which needs to be above the unity.

$$^{6}Li + n \rightarrow {}^{4}He + T + 4.8MeV \tag{3.1}$$

$$D + T \rightarrow {}^{4}He + n + 17.6MeV \tag{3.2}$$

$$TBR = \frac{Tritium\ Bred}{Tritium\ Burned} \tag{3.3}$$

When developing components and studying new concepts for DEMO, the tritium self-sufficiency must keep ensured. Recently a new concept from the Ion Cyclotron Range of Frequencies (ICRF), one of the auxiliary heating systems, consisting in a distributed antenna integrated in blanket, has identified to be very promising.

The project has the main objective to quantify the loss of Tritium Breeding Ratio (TBR) when implementing this antenna in a DEMO reactor, and to verify that it is still above the unity. For that, neutronics simulations with Monte Carlo transport technique have been performed and, with the results, the feasibility of this concept for DEMO can be discussed.

Nevertheless, and due to the fact that some DEMO parameters may change in the future, the scope of this project goes further and includes a parametric analysis on some of the parameters which strongly affect the TBR, such as the poloidal position of the antenna or its depth used in the blanket, between others. The comparison between the different breeding blanket concepts considered for DEMO is also included. This includes the Helium Cooled Pebble Bed (HCPB), the Helium Cooled Lithium Lead (HCLL) and the Water Cooled Lithium Lead (WCLL) blanket concepts.

The scope is enough to allow an estimation of the change on the loss of TBR if some parameters are reasonably biased and also gives guidelines about how much should one be concerned about the TBR when developing the antenna. By now, going further would be probably a waste of time because it is too soon to go into detail and the range of possibilities would be too wide.

4. Theory

This chapter introduces the theoretical part of the work: starting from what is nuclear fusion, and followed by the basics about plasma heating, the components of a tokamak and ending with neutronics. This overview of the field allows to better understand the objective and the contribution of this work.

4.1. Nuclear Fusion: Introduction to the field

Nuclear energy is being developed since the second half of 20th century [Euratom, 2015]. There are two totally different ways to get energy; fission and fusion. The principle of fission is to use a neutron to break a heavy atom into two or more lighter atoms. The principle of fusion is to fuse two light atoms into a heavier atom. It is possible to get energy from these two reactions because, for both of them, the final configuration has a smaller total mass of all components due to a bigger binding energy per nucleon and the difference of mass is released in energy. This can be seen in Fig. 4.1.

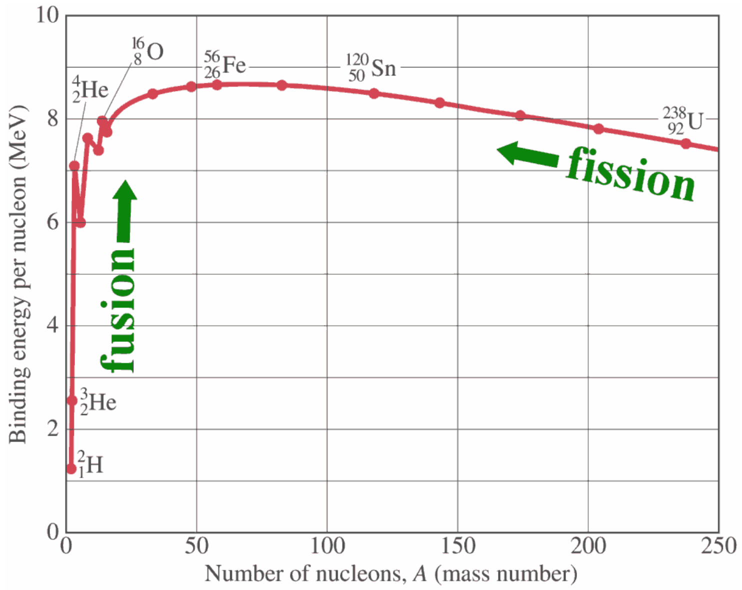

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Figure 4.1 Binding energy per nucleon

4.1.1. Nuclear Fission

Fission is the nuclear energy already implemented nowadays with several hundreds of nuclear fission reactors working worldwide. The fuel is ^{235}U. When bombarded by a neutron, the uranium fissions after having captured the neutron, and the uranium splits into two or more light weighted atoms. Some neutrons are released, typically between 2 and 3, and are used to induce more fission reactions and start a chain reaction. The concept can be seen in Fig. 4.2.

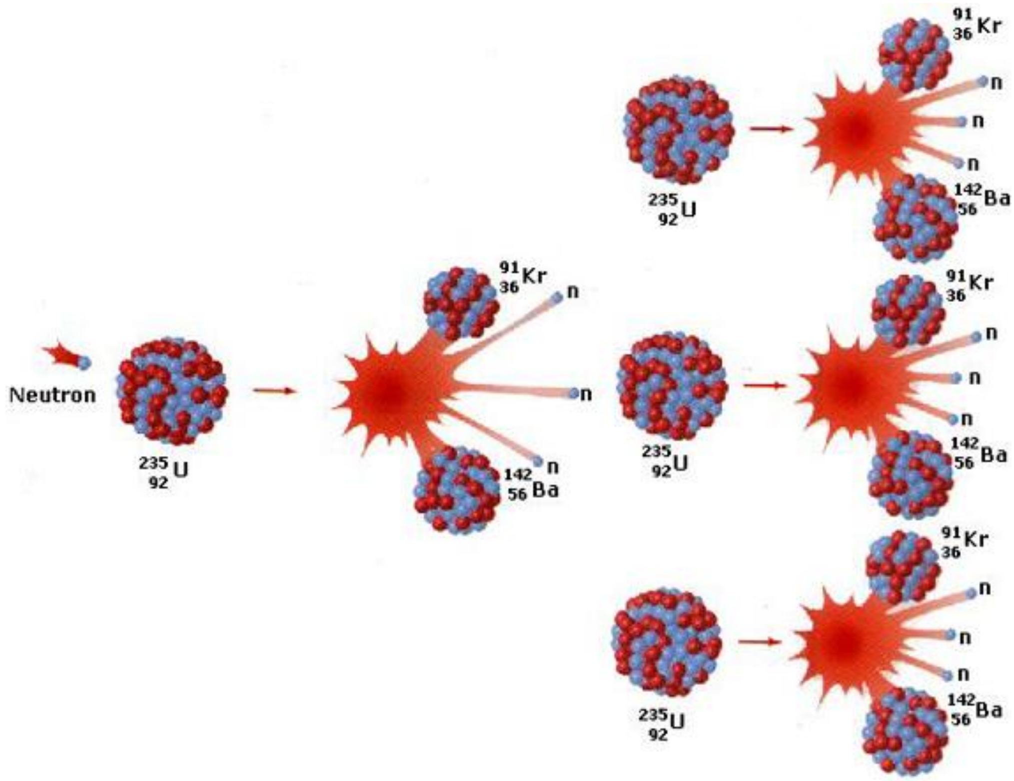


Figure 4.2 Nuclear fission chain reaction

There are two main problems with nuclear fission. In one hand, the chain reaction must be strictly controlled or the energy produced can exponentially increase and end up in a catastrophe. In the other hand, fission waste is highly radioactive for a lot of time. In case of accident and shutdown of the reactor, energy is still released and it needs to be removed by cooling. When the fuel is removed from the reactor, it needs to be treated and eventually buried. This is not sustainable.

4.1.2. Nuclear Fusion

Fusion is the reaction that occurs in the stars and in particular the Sun. There are still no commercial fusion reactors in the world because this technology is still being developed. Fuel, as presently foreseen, is deuterium and tritium (there may be other fusion reactions in the future) [Dies, 2012] and the reaction produces an atom of helium and one neutron. This reaction can be seen in Fig. 4.3.

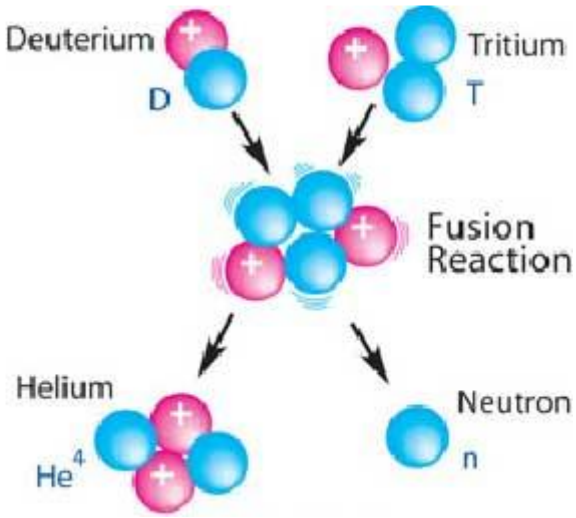


Figure 4.3 Nuclear fusion reaction

Fusion, in contrast with fission, is intrinsically safe. It is very difficult to maintain a steady-state operation and if something goes wrong the reaction stops, and thus the energy production is automatically reduced to zero. Apart from that, the waste of the reaction is not radioactive at all, and the only radioactive element involved is tritium, which is fuel and has a half-life of only 12.3 years (the half-life of ^{239}Pu from nuclear fission is 24100 years). Components of the reactor can become radioactive due to neutron bombardment (depending on which materials the reactor is made of).

The problem with fusion is that it is much more complex than in fission to create a commercial reactor. There are two main problems in fusion; temperature and confinement. In order for fusion reactions to occur, the fuel must be heated up to about 150 million degrees. This temperature is needed for the fusion production to be above the unavoidable radiation losses. Sufficient confinement time and plasma density is needed for the energy production to compensate for the energy losses. At the high temperature the electrons have enough energy to leave the atom and the gas changes to plasma. Not even the strongest material on Earth can handle this temperature, hotter than the Sun. Hence, plasma must be confined by electromagnetic fields dense enough to allow fusion reactions.

From the two confinements that have been considered, magnetic and inertial confinement, the first one is presently the best studied and developed. The most effective magnetic configuration is toroidal with the magnetic field curved to form a closed loop. Combined with the toroidal field there is a perpendicular field component (poloidal field) and the result is a magnetic field with helical lines that confine the plasma.

Two types of toroidal concepts have been more developed than the rest; tokamaks and stellarators. Tokamaks (*TOroidalnya KAmera ee MAgnetnava Katushka*) have a toroidal field created by a series of coils evenly spaced around the torus-shaped reactor, and the poloidal field is created by a current in the plasma, itself created by induction through a central solenoid and a system of horizontal coils typically outside of the toroidal magnet structure. Additional coils are used to provide a vertical field needed for the equilibrium and for plasma shaping. An example of a tokamak can be seen in Fig. 4.4.

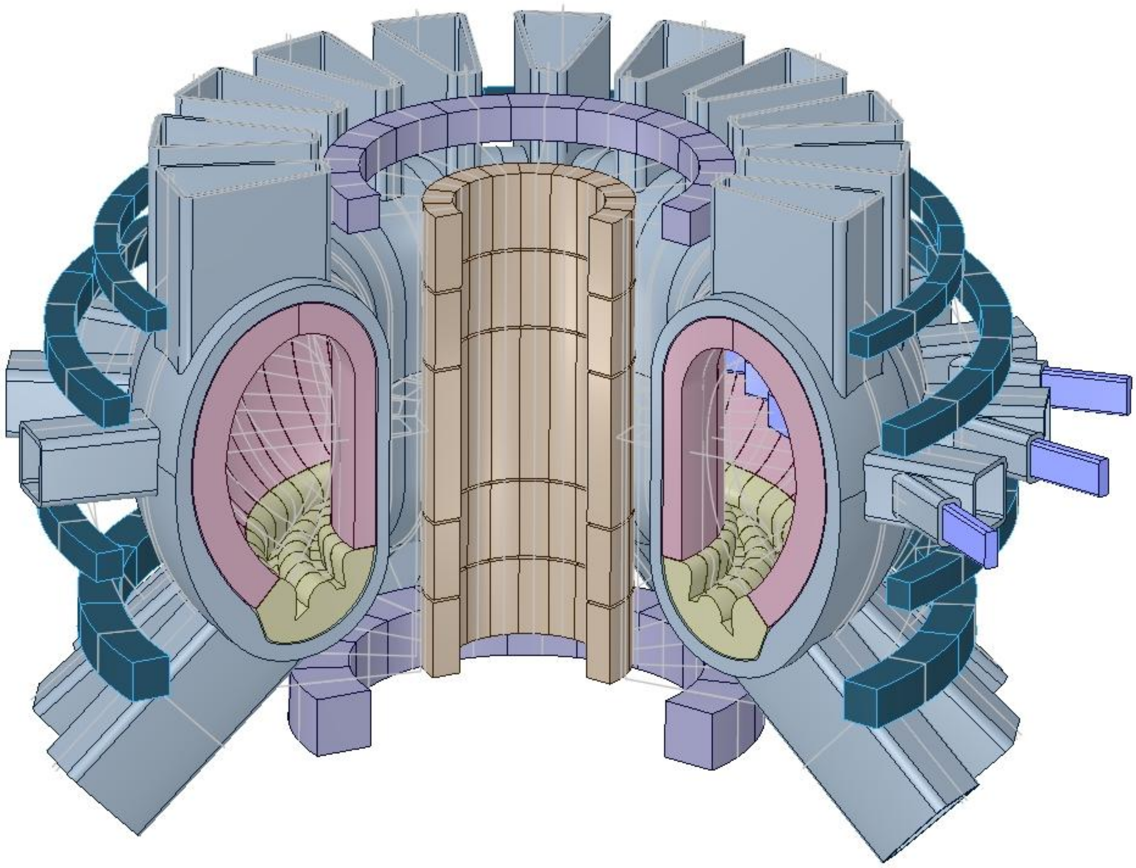


Figure 4.4 DEMO tokamak reactor [ref]

A stellarator uses helical shaped coils to produce the helical lines of force, and thus they do not require inducing a current in the plasma.

As can be seen in Fig. 4.3, the fuel for fusion is deuterium and tritium. Both are isotopes of hydrogen, ^{2}H and ^{3}H respectively. Deuterium can be found in nature, with an abundance of 0.015% in hydrogen (in sea water). Tritium, in the other hand, is radioactive and thus it needs to be produced. The main reaction in the plasma is Eq. (4.1).

$$ {}_{1}^{2}H + {}_{1}^{3}H = {}_{2}^{4}He + {}_{0}^{1}n \qquad (4.1)$$

4.1.3. Nuclear Fusion Roadmap

Fusion research started properly in the 1970s [Euratom, 2015] and it has been developed in different parts of the world, including Europe. The European fusion roadmap for the future is based in three key elements:

- The ITER (International Thermonuclear Experimental Reactor), the largest experimental tokamak, being built by an international nuclear fusion research organization. The project is funded and run by the European Union, India, Japan, China, Russia, South Korea and the United States. The facility is located in Cadarache, France, and the agency in charge of the European contribution to the project, Fusion for Energy (F4E), is located in Barcelona.

- DEMO (DEMOnstration power plant), a single step between ITER and a commercial fusion power plan. It is a prototype of a power-producing fusion reactor, although not necessary fully technically or economically optimised.

- The International Fusion Materials Facility (IFMIF), for material qualification under intense neutron irradiation, which will work in parallel with ITER.

The roadmap is separated into three periods with distinct main objectives:

1) Horizon 2020 (2014-2020) with five main goals:
   a) Construct ITER within scope, schedule and cost.
   b) Secure the success of future ITER operation.
   c) Prepare the ITER generation of scientists, engineers and operators.
   d) Lay the foundation of the fusion power plant.
   e) Promote innovation and EU industry competitiveness.

2) Second period (2021-2030):
   a) Exploit ITER up to its maximum performance and prepare DEMO construction.

3) Third period (2031-2050):
   a) Complete the ITER exploitation.
   b) Construct and operate DEMO.

Horizon 2020 milestones and resources have been defined in detail, while a global evaluation is given for the second period and the third one is only outlined.

ITER and DEMO are both tokamaks, and this work is based on the second one. An example of this reactor can be seen in Fig. 4.4.

4.2. Plasma heating:

As was explained in Chapter 4.1.2, the plasma in a tokamak must be heated up to around 150 million degrees or, what is equivalent, up to around 13 keV. In a tokamak there is an intrinsic heating method called Ohmic Heating. The current, induced to the plasma, heats it by the Joule effect. With this method it is possible to heat the plasma up to 2 or 3 keV, but when the temperature increases the resistivity of the plasma decreases, so less power can be coupled. A solution would be to increase the induced current but there is a limit to it due to instabilities.

In a tokamak, every heating method apart from Ohmic Heating is called an Auxiliary Heating Method (AHM). One of the first ones used was the Adiabatic Compression. If the electromagnetic field is increased the volume decreases. If this process is adiabatic, i.e. without external loss, then the temperature and the pressure increase. The problem with this AHM is that there is also a maximum field; it is therefore barely used nowadays.

The main AHS are the Neutral Beam (NB) and the radiofrequency heating. The last one has two main lines of development, the ECRH (Electron Cyclotron Resonance Heating) and the ICRF Heating (Ion Cyclotron Range of Frequency Heating). With these methods it is possible to achieve the required temperature necessary for the fusion reactions.

4.2.1. Neutral Beam

The idea is to introduce a beam of high-energetic atoms into the plasma. First of all, atoms are ionized and accelerated with an electric field. When they have the desired energy they go through a neutralizer chamber where they capture electron(s) to become neutrals. The reason why they have to be neutral is that, as such, they will not be affected by the magnetic field when entering the plasma and thus will be able to reach the center. After being neutralized they are send to the plasma. When entering the plasma they get ionized and transfer their energy to the other ions. A sketch about this process can be seen in Fig. 4.5.

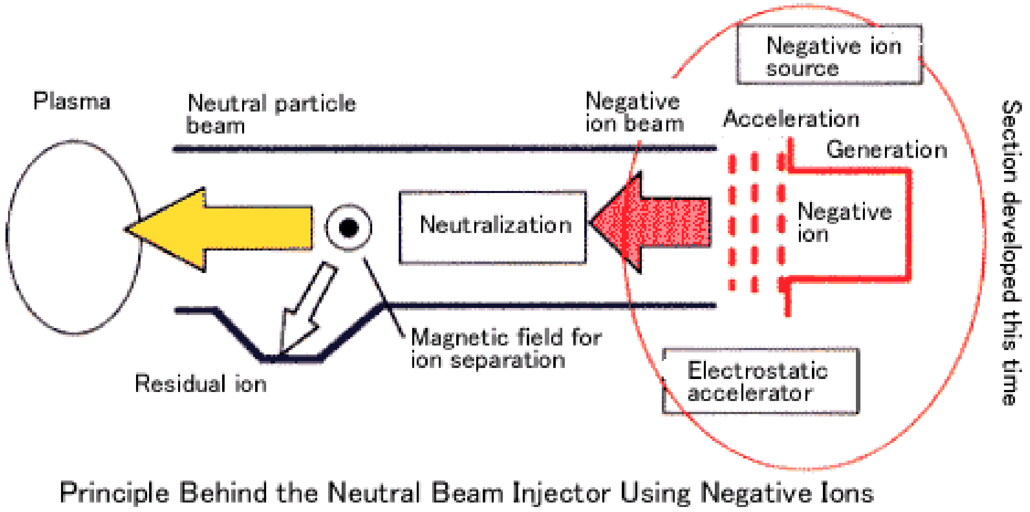


Figure 4.5 Neutral Beam auxiliary heating method sketch

4.2.2. Radiofrequency Heating:

This method is based on using electromagnetic waves that interact with the plasma. As the particles in the plasma are ionized they highly respond to these waves. In particular, a resonance effect can occur when the wave frequency corresponds to a resonance frequency of the motion of the particle. The amplitude of the motion is then amplified. The main oscillations sought are the cyclotron ones, corresponding to the rotation of the particles. If the resonance with the cyclotron motion of the electrons is used then the heating method is called Electron Cyclotron Resonance Heating (ECRH) and the frequency of the waves is in the range of 50-100 GHz. If the resonance with the cyclotron motion of the ions is used, then the heating method is called Ion Cyclotron Range of Frequencies (ICRF) and the frequency of the waves is in the range of 50-100 MHz. This work is about antennas using this last mechanism. In Fig. 4.6 there is an example of the ICRF system developed for ITER seen from the inside of the tokamak.

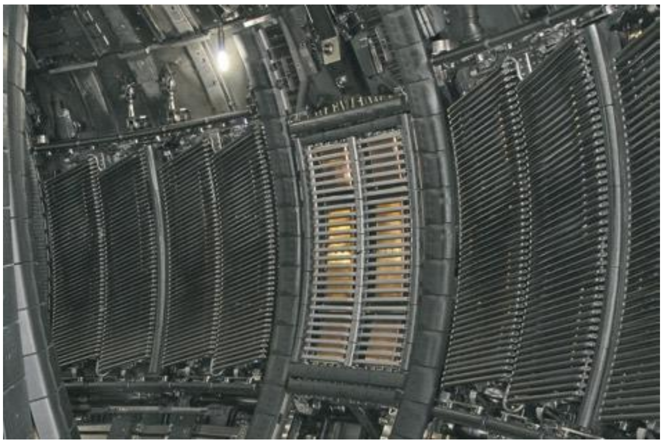


Figure 4.6 Ion Cyclotron Range of Frequencies Antenna for ITER

4.3. The DEMO tokamak:

The DEMO tokamak is composed of different parts, which will be detailed in this section. The blanket is treated separately in detail in the second part of this section because it is particularly important in this work.

4.3.1. Parts of the reactor:

The geometry of a tokamak can be divided into two groups; in-vessel components and out-vessel components. The difference relies on whether the part is inside the vacuum vessel or outside it. A sketch of all major components can be seen in Fig. 4.7.

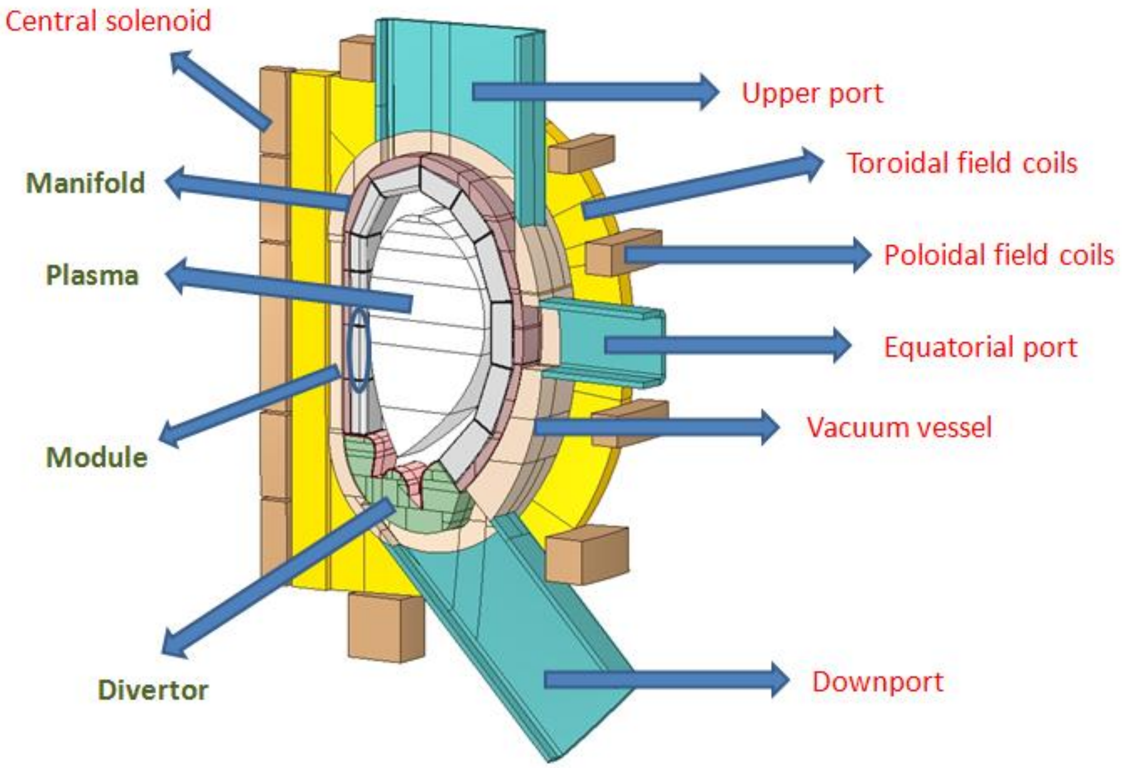


Figure 4.7 Cross-section of a typical DEMO tokamak indicating the main components (Ref. ?)

The combination of the toroidal field coils, the poloidal field coils and the central solenoid provides the electromagnetic field that the plasma requires, as was explained in Chapter 4.1.2.

The vacuum vessel works both as structural material and shielding for the coils, which have a limit on radiation that can receive.

The upper, equatorial and down port are the only openings through the vacuum vessel to access the in-vessel part because DEMO presents a more compact in-vessel geometry than ITER.

For the in-vessel components, it is possible to separate them into the divertor, the modules and, of course, the plasma.

The divertor has the function of removing the impurities and reaction products from the fusion reaction while the reactor is operating.

4.3.2. The in-vessel modules and the blanket

The most important part for this work is the module, which is detailed in Fig. 4.8. Each of these modules is composed by the First Wall (FW), the blanket and the manifold.

The manifold is not included in Fig 4.8, but it has been included in Fig. 4.7, to make Fig 4.8 more illustrative

Facing the plasma there is the First Wall (FW) which is separated into a 2 mm first layer of Tungsten (W) and a second 25 mm layer of steel. The first layer is the Plasma Facing Material (PFC) and Tungsten has being replacing carbon lately because it has a high melting point, a low erosion rate and small tritium retention. The second steel layer is part of the structural material of the module.

The manifold is the system that feeds the blanket with coolant, power or what is necessary (it can depend on the type of blanket). It is usually combined with a supporting structure for the attachment of the module to the VV.

The blanket is the part of the DEMO tokamak located between the FW and the Manifold (see Fig. 4.8). Its purpose is to breed tritium to use it again as fuel and to extract energy from the neutrons. It can also partly act as shielding although at a very low efficiency.

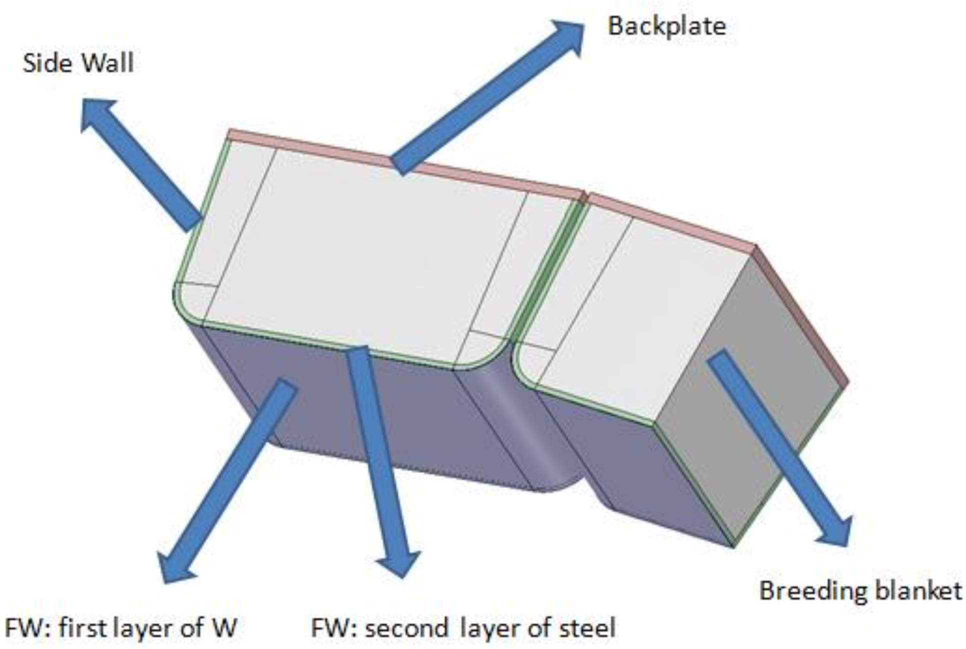


Figure 4.8 DEMO module (in-vessel component) without the manifold included (Ref. ?)

The blanket is separated in modules with the Multi Module Segments (MMS) concept [EFDA, 2013], used for the first time in DEMO. Each blanket module is independent from the rest and 6 modules are gathered in a poloidal segment, which is attached to the vacuum vessel (VV). Each blanket sector (16 in total) is composed by 2 inboard segments, the Left Inboard Blanket Segment (LIBS) and the Right Inboard Blanket Segment (RIBS), and 3 outboard segments, the Left Outboard Blanket Segment (LOBS), the Central Outboard Blanket Segment (COBS) and the Right Outboard Blanket Segment (ROBS). Fig. 4.9 will help to understand the idea. This is a very compact configuration where the modules are introduced and extracted through the upper port as part of a segment, as can be seen in Fig. 4.10.

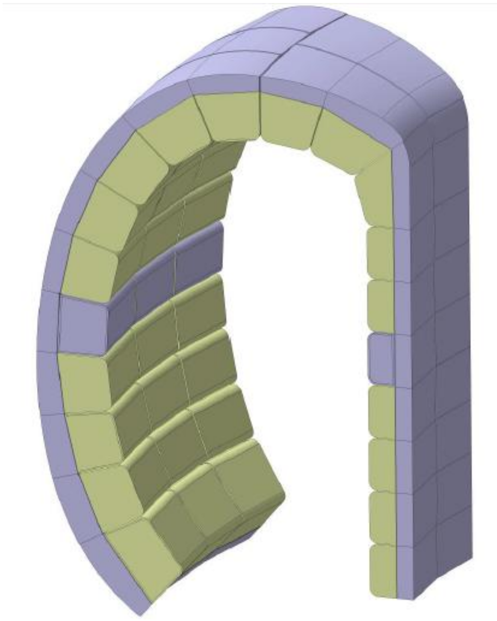


Figure 4.9 Blanket sector of a DEMO reactor; Multi Module Segment concept illustrated

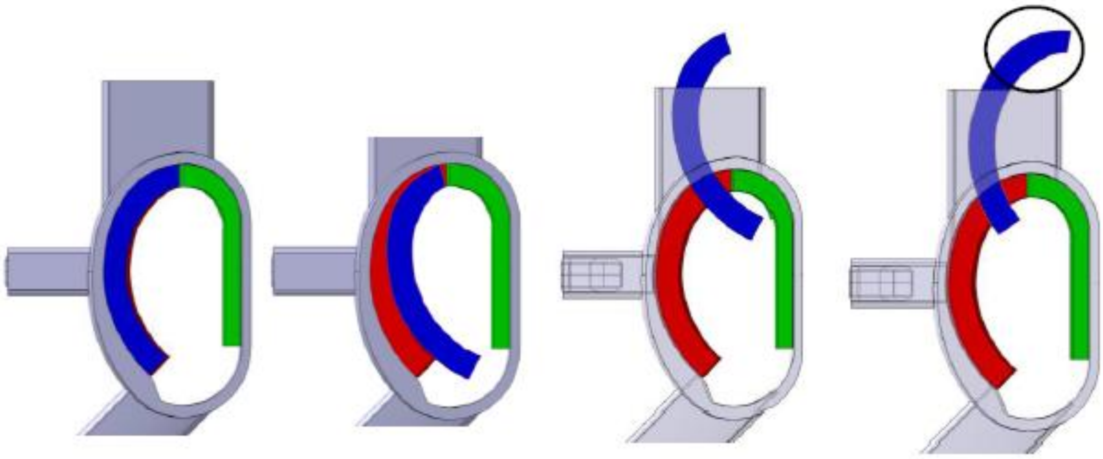


Figure 4.10 Blanket segments removal process

Different types of blanket are being studied and developed. The Helium Cooled Pebble Bed (HCPB) and Helium Cooled Lithium Lead (HCLL) will be tested in ITER and are therefore the strongest candidates for DEMO at the moment [Poitevin, 2011]. However, the Water Cooled Lithium Lead (WCLL) it is also a good candidate for DEMO due to water's capability of cooling and moderating [Dies, 2011].

Helium Cooled Pebble Bed (HCPB) blanket concept:

This solid blanket is composed by pebble beds made of either Li4SiO4 ceramics or Beryllium that are separated by cooling plates with high pressure Helium gas as coolant (8 MPa). The first acts as tritium breeder with its Li enriched in Li-6 due to reaction (4.2) and the second acts as neutron multiplier (see Fig. 4.11) due to reaction (4.3).

^{6}Li (n,alpha)t + 4,78 MeV (4.2)

^{9}Be (n,2n)2α – 1,57 MeV (4.3)

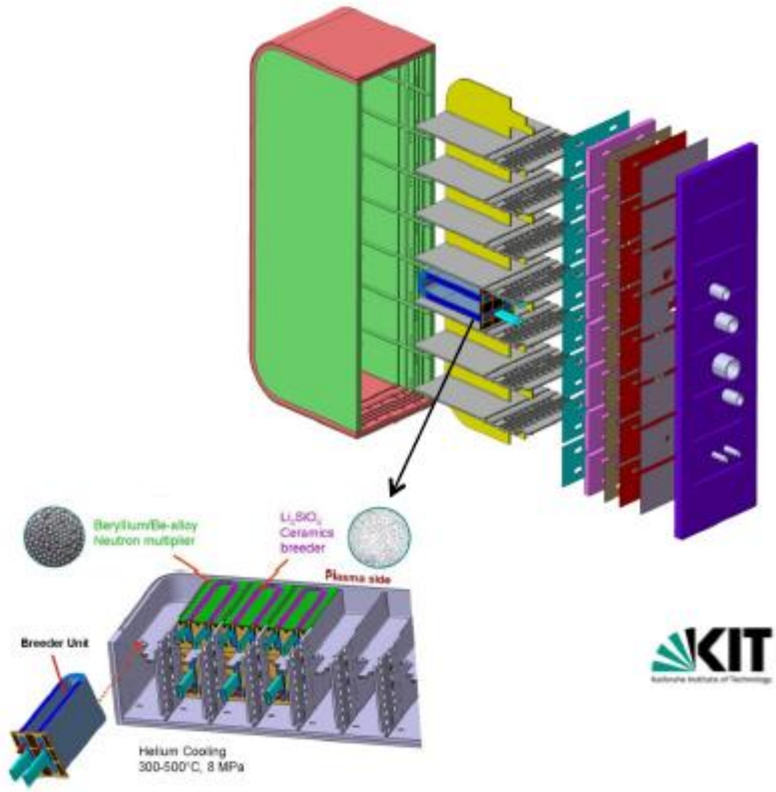


Figure 4.11 DEMO Helium Cooled Pebble Bed blanket [Li Puma, 2012]

Beryllium is a superior neutron multiplier. It has the highest neutron multiplication power because it has a relative low threshold (1.75 MeV) and then a neutron emitted from this reaction can have sufficient energy to start another n→2n reaction with Be. Furthermore, its low mass combined with its neutron absorption cross-section makes Be a great moderator. This is really advantageous due to the high Li-6 cross-section for reaction (1) at low energies.

For cooling plates, as well as for stiffening material required for structural purposes, reduced activation ferritic-martensitic steel Eurofer is used with a Fe content of around 90% in weight. Its main reaction is (4.4) and it is the major parasitic neutron absorption reaction in the blanket, although it significantly contributes to the heat generation.

$$^{56}Fe\ (n,gamma)^{57}Fe + 7.65MeV \qquad (4.4)$$

Helium Cooled Lithium Lead (HCLL):

In contrast to HCPB, this is a liquid blanket. It uses a liquid eutectic allow of lithium and lead cooled by high pressured helium. Lithium needs to be highly enriched in Li-6 (up to 90%) and acts as tritium breeder, whereas lead acts as neutron multiplier. Eurofer is again used as structure material. The concept can be seen in Fig. 4.12.

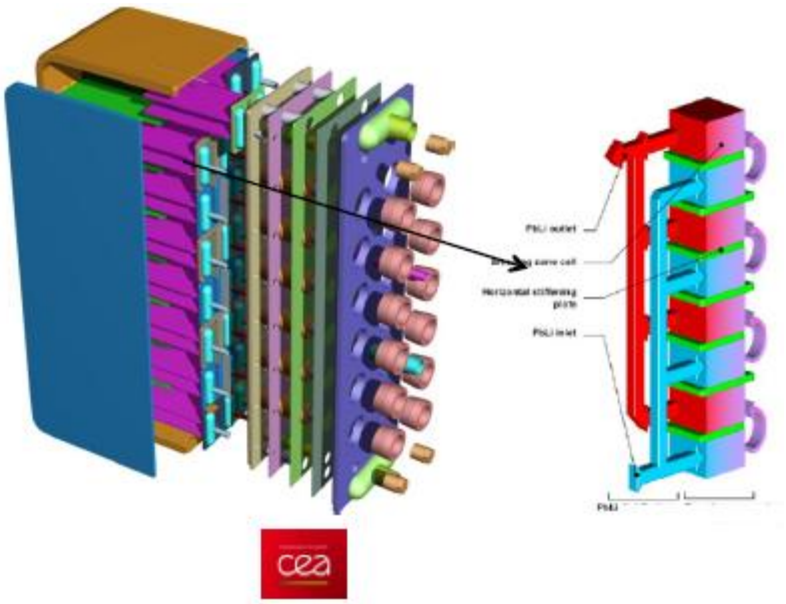


Figure 4.12 DEMO Helium Cooled Lithium Lead blanket concept [Li Puma, 2012]

Pb-Li alloy could be used as coolant but this is not desired. It would need a high speed circulation, and Magneto Hydro effects induced in the flowing liquid metal due the high magnetic fields of the tokamak would create high pressure drops. Therefore, only a slow circulation is used to extract the tritium from it.

On the one hand Li combines a low neutron cross-section for fast neutrons and a low mass, which leads to a high average mean free path (15-20 cm). On the other hand, Pb combines a high elastic scattering neutron cross-section and a high mass, which leads to many scattering events without significant loss of kinetic energy of the neutrons. The liquid blankets with this composition usually need to be bigger to produce enough absorption in lithium for the reaction (4.2) to guarantee sufficient tritium breeding.

Water Cooled Lithium Lead:

This is also a liquid blanket that is cooled by water instead of helium. The high cooling capability of water is already known but water is also a strong moderator due to the hydrogenous content and its higher density (it is liquid and He is gas). It also uses an eutectic alloy Pb-Li both as tritium breeder and neutron multiplier. Eurofer is again used as stiffening material and the cooling water is inserted at 15.5 MPa and 325ºC. This concept can be seen in Fig. 4.13.

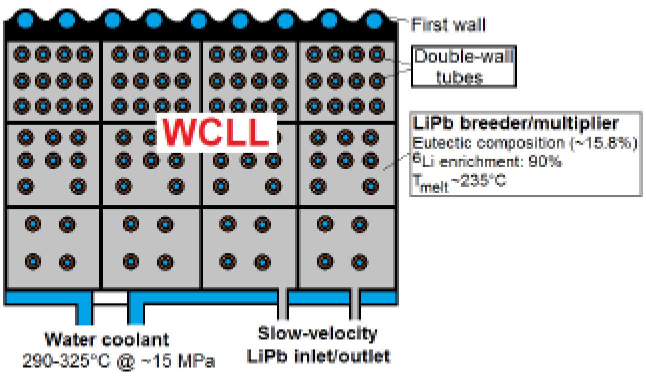


Figure 4.13 DEMO Water Cooled Lithium Lead Blanket [Li Puma, 2012]

4.4. Neutronics in Nuclear Fusion. The Tritium Breeding Ratio

As was explained in Chapter 4.1.2, the main reaction in the plasma of a tokamak is Eq. (4,5), where a neutron is released. This neutron gets the 80% of energy from the reaction, 14.1 MeV.

$$ {}^{2}_{1}H + {}^{3}_{1}H = {}^{4}_{2}He + {}^{1}_{0}n \tag{4.5} $$

As a neutral particle, the neutron escapes from the confinement and diffuses through matter undergoing various nuclear reactions. Hence, neutronics in fusion is the transport of 14 MeV neutrons through matter, including mathematical representation of the propagation process with all nuclear interactions taking place. Neutron and photon transport are described with a probabilistic or deterministic approach which provides the neutron and photon distribution in space and energy. The Tritium breeding, the nuclear heat generated and deposited, the transmutation/activation of all materials, or even the radiation induced damage can then be assessed.

There are some strong differences between fission neutronics and fusion neutronics. Neutrons from a fission reaction are released in a reactor with an average energy of 2 MeV, whereas neutrons from a fusion reaction in a tokamak are released at 14 MeV. The energy spectrum involved in calculations is higher, so all the nuclear cross-section data is higher (and less accurately known). Furthermore, in fusion there is a strongly anisotropic transport from the plasma towards the outside the tokamak. The geometry of a tokamak is also more difficult than a nuclear fission reactor, resulting in more complex neutronics calculations.

4.4.1. Nuclear reactions

It is not the aim of this work to explain in depth the basics of the neutron transport. Only the two most important nuclear reactions involved will be explained: elastic scattering and neutron absorption.

- *Elastic scattering:*

It is the process in which a neutron collides with an atomic nucleus and there is a transfer of energy and momentum, as can be seen in Fig. 4.14. Both elements, the neutron and the atomic nucleus, can be represented by hard spheres in this process and thus can be described by classical mechanics. A neutron with high energy transfers kinetic to the colliding nucleus, which is in thermal equilibrium. Then the neutron is slowed down (this is also called moderated) to a lower energy. The maximum energy transfer is shown in Eq. (4.6).

$$\Delta E_{max} = E_n \cdot \left[1 - \left(\frac{M-m_n}{M+m_n}\right)^2\right] \tag{4.6}$$

M = mass of the nucleus, m_n = neutron mass, E_n = initial kinetic neutron energy

Low mass nuclei are thus efficient neutron moderators, so hydrogenous materials such as water are the most efficient moderators. The larger the amount of material with a low mass in a fusion reactor, the faster moderation will occur.

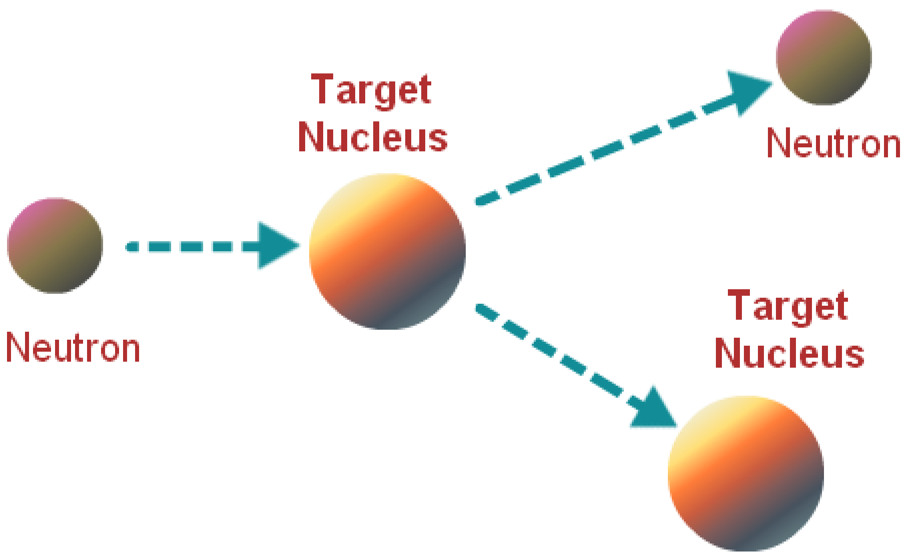


Figure 4.14 Elastic scattering process

- *Neutron absorption:*

It is the process in which a neutron is absorbed by the colliding nucleus X(A,Z), with mass number A and nuclear charge Z, forming a new nucleus X(A+1,Z). The new nucleus is highly excited and decays by the emission of various particles or by radiation. Different possibilities can occur. A particular one is in Fig. 4.15 where capture followed by emission of photons is shown.

The emission of photons results in a nucleus X(A+1,Z) as reaction product and it is called a (n,γ) reaction. It is the source of the photon radiation in a fusion reactor. One of the most important examples of this reaction is the (n,γ) reaction on Fe-56 to produce Fe-57 plus a gamma with an energy of 7.65 MeV. This is the main parasitic reaction because steel is employed as structural material.

Another possibility is the emission of two neutrons, resulting in a product nuclei X(A-1,Z) and usually also gamma radiation. The reaction is called inelastic because the total kinetic energy of the particles is not conserved since some kinetic energy of the incident neutron is converted into electromagnetic radiation energy. The main use of this absorption in fusion reactors is to multiply neutrons in the blanket. Be and Pb are used for these (n,2n) reactions to produce two secondary neutrons of lower energy from one neutron with high energy. This multiplication is necessary to compensate the parasitic neutron losses and achieve a sufficient Tritium production.

Finally, there is also the possibility to emit charged particles (p, d, t, He-3, α) producing nuclei with a lower atomic number (Z-1 or Z-2). Charged particles are generally not transported but assumed to be locally absorbed. This means that their kinetic energy is assumed to be entirely transferred to the material as heating energy at the location of the reaction. The most important example is the Li-6(n,α)t reaction which produces a triton while an alpha particle is released with 4.78 MeV.

The process occurring depends on the colliding nucleus and the energy of the neutron. It can’t be predicted, but the probability of having one reaction or another one is given by the cross-sections, which can be found in different Nuclear Fusion Data Libraries [NEA, 2015].

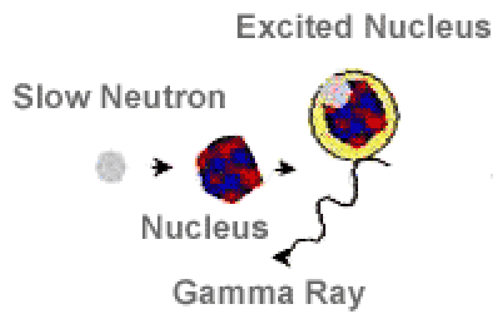


Figure 4.15 Neutron absorption reaction with emission of γ

4.4.2. Tritium Breeding Ratio

It was explained in Chapter 4.1.2 that tritium is radioactive. Since it has a half life of only 12.3 years it almost does not occur in nature and needs to be produced. It is already clear that DEMO needs to be self-sufficient in tritium, which means that the entire amount consumed in the plasma will need to be generated in the same reactor. This is possible with lithium due to reactions (4.7) and (4.8) from both of its stable isotopes.

$$^{6}Li + n \rightarrow \alpha + T + 4.786\ MeV \qquad (4.7)$$

$$^{7}Li + n \rightarrow n' + \alpha + T - 2.467\ MeV \qquad (4.8)$$

In Fig. 4.16 the microscopic cross-section for both reactions is shown. Lithium is typically enriched in ^{6}Li because, on one hand, there is no energy threshold (for ^{7}Li it is 2.467 MeV) and, on the other hand, the cross-section is strongly increasing with decreasing energy up to very high values.

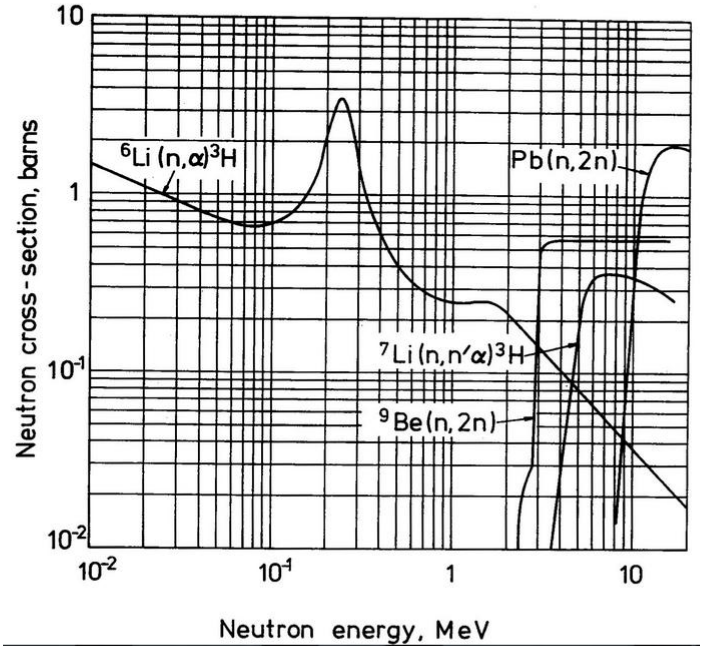


Figure 4.16 Microscopic cross-sections for tritium production [Kaye&Laby, 2008]

Around 10^{22} neutrons/s are released in the plasma towards the FW. To breed tritium they need to be absorbed in the blanket by lithium under reaction (4.7) or (4.8). Some neutrons will undergo other parasitic reactions such as some shown in Chapter 4.4.1 and therefore they will no longer be available to produce tritium. Neutron multipliers such as Be or Pb are used to increment the number of neutrons in order to achieve tritium self-sufficiency.

The Tritium Breeding Ratio (TBR) is the parameter used to quantify the above mentioned self-sufficiency. The main reaction in the plasma is reaction (4.9), which consumes one triton and releases one neutron. The main reaction to produce tritium is (4.7), which consumes one neutron and produces one tritium. The TBR is defined, then, as the tritons produced in the blanket over the neutrons produced in the plasma, and it needs to be greater than 1 in order to have a reactor self-sufficient in tritium.

$$ {}_{1}^{2}H + {}_{1}^{3}H = {}_{2}^{4}He + {}_{0}^{1}n \qquad (4.9) $$

Actually some margin is required to account tritium losses and uncertainties, so typical design targets set the global TBR required in the range of 1.05 to 1.15. The TBR can be calculated as follows:

$$TBR = \frac{\int N_{^6Li} \cdot {}^{6Li}\sigma_{n,\alpha}\phi dV + \int N_{^7Li} \cdot {}^{7Li}\sigma_{n,n'\alpha}\phi dV}{N_\phi} \qquad (4.10)$$

N_φ is the number of source neutrons produced in the (d,t) plasma, N is the density of the material (either ^{6}Li or ^{7}Li), σ is the microscopic cross section and φ is the neutron flux.

4.4.3. Particle transport in matter

In order to study different parameters such as power generation, radiation shielding and, of course, tritium breeding performance, one needs to know the particle distribution in space and energy for both neutrons and photons. With nuclear cross-section data describing the interaction processes of particles and atom nuclei, there are two totally different methodological approaches to calculate the desired parameters: the deterministic approach and the probabilistic approach.

- *Deterministic approach (macroscopic description):*

The Boltzmann transport equation is used, Eq. (4.11), balancing particle gains and losses in infinitesimal phase space element.

$$\Omega \cdot \nabla\Psi(r,E,\Omega) + \Sigma_{tot}(E,r) \cdot \Psi(r,E,\Omega) =$$

$$\int_{4\pi} d\Omega' \int_0^\infty dE' \cdot \Sigma_s(r,E' \to E, \Omega' \to \Omega) + Q(r,E,\Omega) \qquad (4.11)$$

The left part of the equation corresponds to the particle losses in phase space element and the right part to the particle gains. They are:

$\Omega \cdot \nabla\Psi(r, E, \Omega)$ Leakage out of volume element

$\Sigma_{tot}(E, r) \cdot \Psi(r, E, \Omega)$ Absorption and scattering in other direction or other energy interval

$Q(r, E, \Omega)$ Direct generation of source particles

$\int_{4\pi} d\Omega' \int_0^{\infty} dE' \cdot \Sigma_s(r, E' \to E, \Omega' \to \Omega)$ In-scattering of particles from other directions and energy intervals

In fusion 175 energy bins of energy are usually used to solve the problem using this method and the equation needs to be solved for all of the energy bins. Geometry is in general very complex and therefore the deterministic approach is not well suited for solving transport problems in fusion technology.

- *Probabilistic approach (microscopic description):*

In this case, a simulation of real physical processes on microscopic level is done with the Monte Carlo method. It is based on the idea of tracking an individual particle from "birth" (in nuclear reaction) to "death" (by absorption or leakage) in the so-called "random walk". A very large amount of random walks are done and the results are averaged. As there is a continuous energy representation of cross-sections, no real approximation is required.

Using geometry cells defined by pre-defined solids or bounding surfaces using combinatorial algebra, any arbitrary 3D configuration of any complexity can be modeled without using meshes. The accuracy is limited by statistical error and the uncertainty of the nuclear data, and a large number of histories are required, which leads to a big computational effort.

Monte Carlo is used in nuclear fusion for neutronics calculations and, hence, it has been used for this work. A deeper explanation of how Monte Carlo works is shown in Chapter 5.3.

5. Problem definition

As one may understand from Chapter 4, nuclear fusion involves a lot of different and complicated processes and thus calculations need to be accurate and representative. In this chapter, the way of how a real tokamak is represented in order to calculate the TBR is shown. First of all the physical features of the antenna, which was explained in Chapter 4.2, is detailed. After that, the DEMO model used and how it is modeled is explained. Finally, the MCNP tool announced in Chapter 4.4, which is the one used for all the calculations of this work, is also explained.

5.1. The Ion Cyclotron Range of Frequencies antenna

It is not the aim of this work to study nor develop the antenna, but to study the effect on the TBR. Hence, only a brief explanation of the benefits of the antenna is explained here.

Typically the ICRF technology requires a launcher placed in the blanket [Dumortier, 2012]. Quite the opposite, the antenna consists in an array of straps placed inside a 360º toroidal slot in the FW from where the power is coupled to the plasma [Bosia, 2014]. Some of these straps are fed and they couple power to the other ones, to finally couple together the desired power to the plasma. This is possible by controlling the amplitude and frequency of the straps fed. In Fig. 5.1 a draft of the antenna integrated in the reactor is shown in order to illustrate the concept.

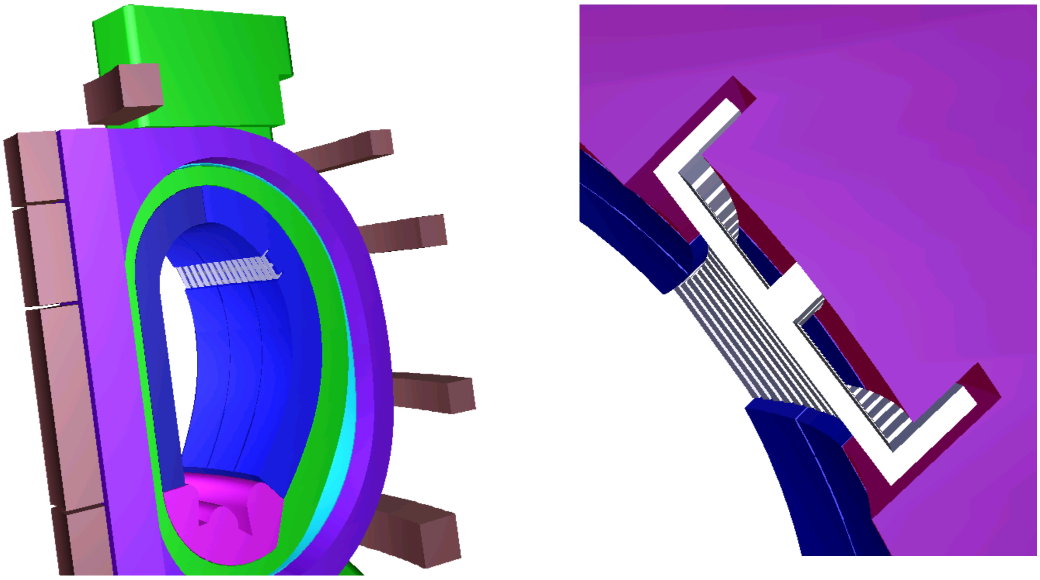
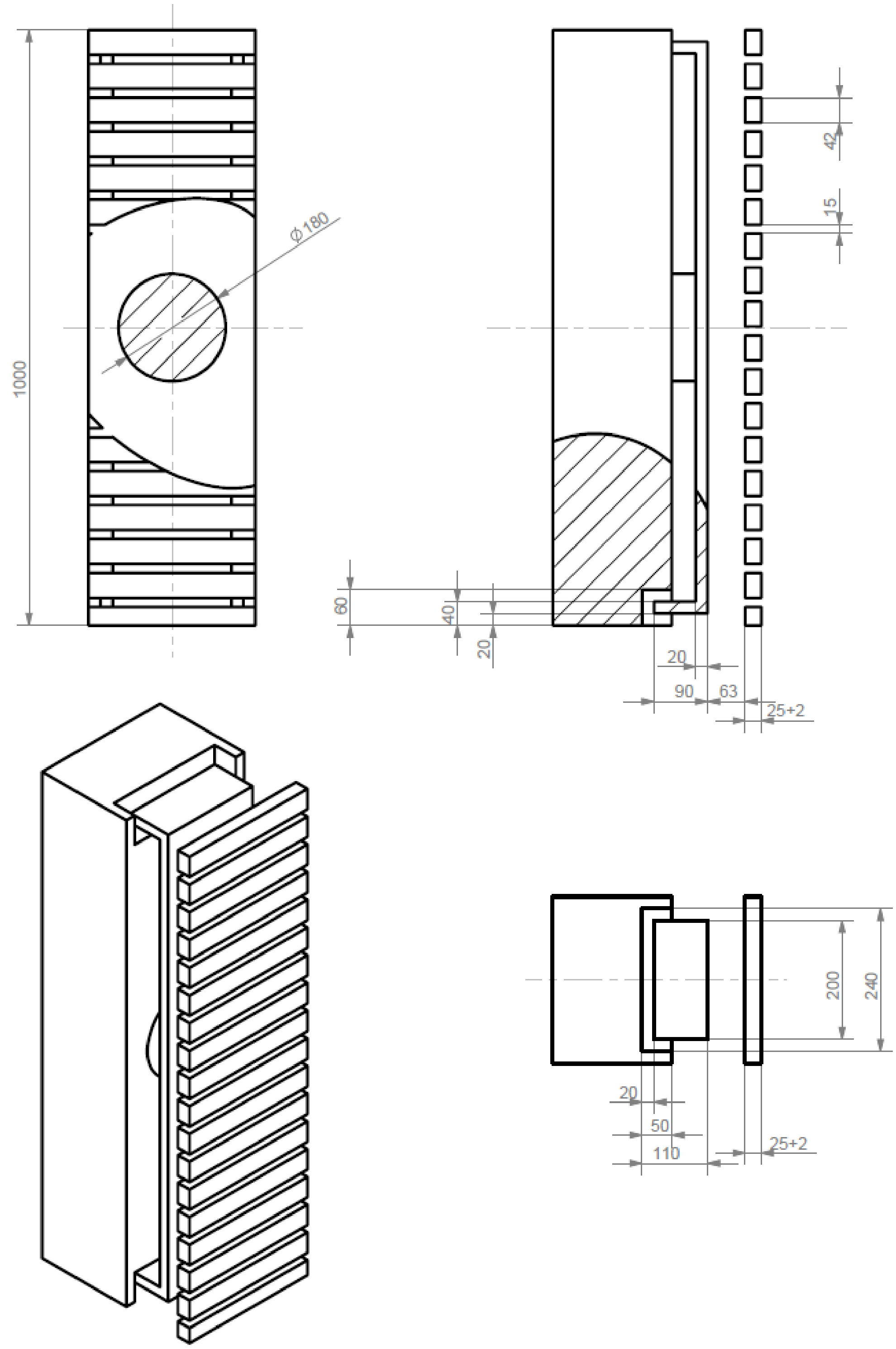


Figure 5.1 Draft of an ICRF antenna integrated in a DEMO reactor

This is a very promising improvement in terms of tritium self-sufficiency, because instead of using a whole port for the device, it uses only a small width of the blanket near the FW. Hence, the rest of the module is still available to breed tritium and the loss of TBR is lower.

As a neutronics work, the importance of the antenna comes from; its appearance (shape and size), its composition and its position. The antenna is, however, under development and part of this work was to find out a preliminary but representative configuration of it. In Fig. 5.2 there is the drawing of the antenna which details the shape and size of it.



Surname	Date	Material	Scale
Garcia Perez	September 2014 - June 2015	Helium cooled Eurofer	1:10
Name	Model		
Albert	Ion Cyclotron Range of Frequencies distributed antenna in a DEMO reactor		

Figure 5.2 Drawing of the ICRF antenna

Although the antenna is not fully defined, there are some conditions that must be foreseen in its development. The IC array must fit the following requirements [Bosia, 2014]:

- <u>The antenna must not impair any blanket function</u>: it has to keep ensuring the tritium self-sufficiency and the capability to the energy from the fusion reaction.

- <u>The antenna must match the blanket modularity and not require extra openings in the vessel</u>: each blanet module is independent from the rest so the antenna can't require an internal connection between modules, as well as it must use one of the already existing ports for the feeding lines.

- <u>The antenna must share the same coolant of the blanket</u>: He or water, the cooling system must be integrated with the one of the blanket.

- <u>The antenna must not increase the complexity of the Remote Handling</u>: the remote handling of the blanket is a complex system through the upper port where the pipes and tubes are weld and reweld outside the VV (Ref. to Coleman). Hence, the remote handling of the antenna must work in the same way.

The final configuration shown in Fig. 5.2 fulfills all these conditions.

For the composition of the antenna, helium cooled Eurofer-97 is used as a first estimation because it is the same than the stiffening material of the blanket and it allows the functionality of the ICRF [Ragona, 2014]. In front of the straps and facing the plasma there is a Faraday Screen (FS) with the composition of the FW (2 mm Tungsten plus 25 mm Eurofer) which is basically the FW with horizontal holes. In Fig. 5.3 the FS can be appreciated. It is 4.2 poloidal cm of FW plus 1.5 poloidal cm holes [Noterdaeme, 2014].

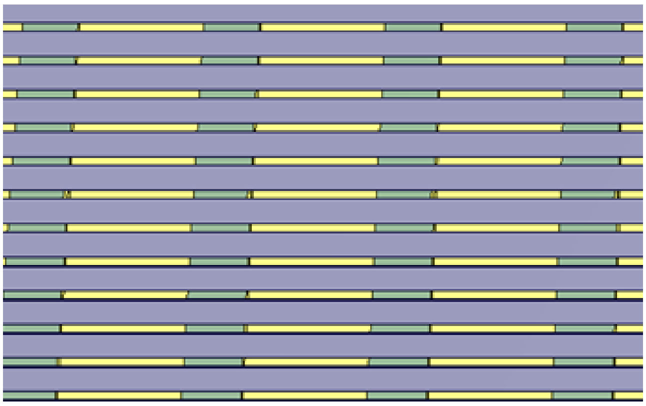


Figure 5.3 Faraday Screen of an ICRF antenna

Due to its functionality, the antenna can be placed in the outboard upper modules as can be seen in Fig. 5.4 [Ragona, 2014]. The final configuration has the antenna placed in the central blue circle in Fig. 5.4, which corresponds to 40º.

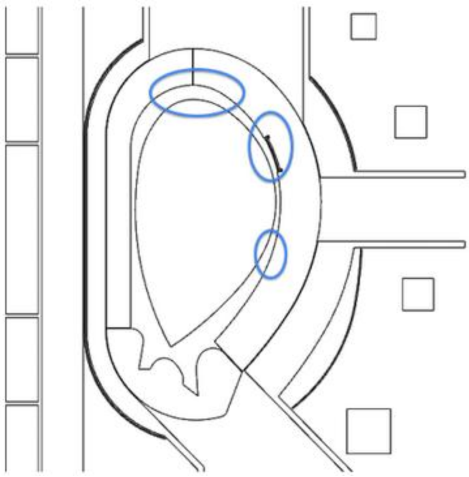


Figure 5.4 Possible locations of the ICRF antenna

It is not clear yet how many straps will need to be fed per sector. As a first assumption 2 fed straps per blanket sector may be considered [Ragona, 2014]. Therefore, 4 feeding lines will be needed per sector. It is still being discussed which will be the suitable material. Copper is a well known conductor but can present problems due to the high temperature and the neutron irradiation in the blanket. The structural copper allow CuCrZr has the operational temperature around 200-350°C and near the FW the temperature can easily reach 500°C. Studies about Eurofer as a transmission line material could be interesting. For the time being, however, the feeding lines are not considered.

5.2. The DEMO reactor modeling

In Chapter 4.3 the parts of a DEMO tokamak where explained. Neutronics analysis are complex and this is enhanced the more complex the model is. As the objective of this work is to calculate the TBR, which occurs in the blanket, some parts of the reactor are not needed in the calculation because their effect on the parameter calculated is neglectable. Following this, the poloidal coils, the toroidal coils and the central solenoid will not be involved from now on. Then, FW (the first 2 mm of Tungsten and the 25 cm of steel), blanket, manifold, divertor (3 different layers), VV and 3 ports (upper, equatorial and down port) are used in the study.

The model used is a DEMO geometry developed in KIT in the frame of the Power Plant Physics and Technology Programme (PPPT) under EFDA but takes into account a recent update conducted in 2014 with the EUROfusion PPPT programme [Pereslavtsev, 2014a]. The recent model consists of 12 modules (banana-shape cross-section). The blanket used is HCPB which was explained in Chapter 4.3.2. Each module consists in a central zone delimitated by boxes on all sides and a backplate in the bottom. In the front part there is the FW with its Tungsten and steel layers. The central zone is filled with an homogeneous HCPB blanket mixture corresponding to the last updated version of KIT, which is 57% Beryllium + 19% Li_4SiO_4 (^6Li enriched up to 60%)+ 15% Eurofer + 9% He.

Due to symmetry, only 11.25º of a full tokamak need to be defined in this kind of calculation, corresponding to half of a tokamak segment. That is 1 inboard segment and 1.5 outboard segments. In Fig. 5.5 the model of the tokamak is shown.

MCNP, which will be explained in Chapter 5.3, allows to create any 3D configuration regardless the complexity by simple geometric cells. Nevertheless, manual modeling of a complex 3D geometry is tedious, time consuming and very error prone. Instead, CAD geometry can be converted into MCNP geometry with certain programs, depending on the working institution. For this work the program used was [SpaceClaim], and the model of the 11.25º tokamak is shown in Fig. 5.5.

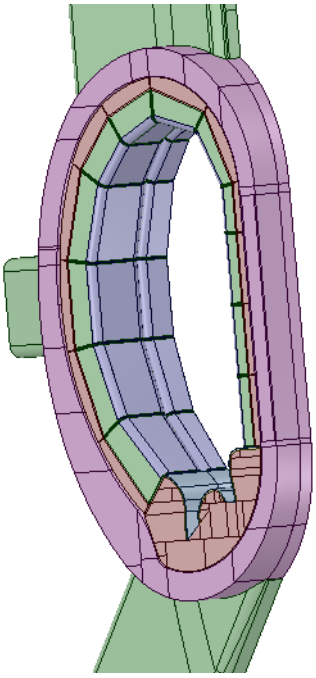


Figure 5.5 CAD model of a DEMO reactor sector visualized in SpaceClaim

For this work, the antenna explained in Chapter 5.1 needs to be implemented in the tokamak CAD model. The implementation process with SpaceClaim can be found in Annex A. With the desired model in a CAD file, it needs to be converted into MCNP geometry in order to run the calculation. The program used for this was the McCad [Lu, 2014] interface and the process of conversion is detailed in Annex B. A comparison between SpaceClaim and McCad interfaces is shown in Fig. 5.6.

McCad returns an input file, which is already compatible with MCNP and has all the information about the model. However, it does not have the information about which type of study the user wants to perform, so the input file needs to be modified to fit the user's requirements. The set up of the input file for the calculations in this work is detailed in Annex C. Only for KIT MCNP users, the details about how to run MCNP are exposed in Annex D.

After the set up of the input file, this is ready to run particles and to make calculations.

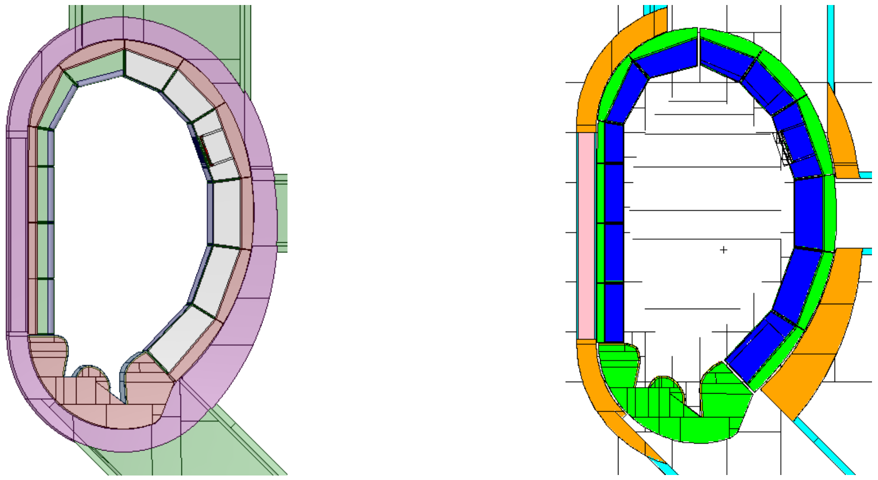


Figure 5.6 Result of the McCad conversion : DEMO 11.25º tokamak with the antenna implemented with SpaceClaim (left) and with MCNP geometry (right)

5.3. Monte Carlo N-Particle (MCNP)

As was explained in Chapter 4.4.3, neutronics calculations in nuclear fusion are made with the probabilistic approach through a MCNP simulation. The version used in this work is MCNP-5 [X-5 Monte Carlo Team, 2005]. The simulation is supported by a nuclear data library for all the cross-sections, and the one used here is FENDL-2.1 [IAEA, 2004].

MCNP is a rather complex simulation technique due to its multiple possibilities. It is not the aim of this work to explain it but a brief overview about its functionality and a few explanation about the options used will be explained here. For more information, the reader is encouraged to read the MCNP manual "*MCNP — A General Monte Carlo N-Particle Transport Code, Version 5*", both Volume I and Volume II, from Los Alamos National Laboratory.

In contrast to the deterministic approach that for example the Boltzmann transport equation gives, which consists in balancing a particle gains and losses in infinitesimal phase space element, MCNP is a simulation of real physical processes on microscopic level with interaction probabilities given by nuclear cross-sections. Basically it tracks individual particle histories from "birth" (creation of the neutron, in the plasma in this case) to "death" (absorption or leakage). When enough histories are made then the average on the results gives the distribution. Continuous representation of cross-sections can be used and thus no approximations are required.

There is no limit on the complexity of the model used because it uses geometric cells defined by pre-defined solids or bounding surfaces using combinatorial algebra. The accuracy is limited by statistical error and the uncertainty of nuclear data. However, a large number of histories are needed (in this work between 10E+07 and 10E+08) and thus a big computational effort as well.

The histories or “random walks” are determined between the definition of all the possibilities a neutron has in every moment and pseudo-random numbers which “decide” what to do. An example of one track would be:

The neutron is “born” in the plasma chamber. The position (source distribution given), the energy (source energy distribution given) and the flight direction (isotropic emission assumed) of the neutron are sampled.

When the neutron is emitted from the plasma, the probability to interact with matter is given by Eq. (5.1).

$$p(l)dl = e^{-\Sigma_t l}\Sigma_t dl \quad (5.1)$$

Setting ξ the random number (0,1] to be the one of Eq. (5.2), then Eq. (3) is found.

$$\xi = \int_0^l e^{-\Sigma_t s}\Sigma_t ds = 1 - e^{-\Sigma_t l} \quad (5.2)$$

$$l = -\frac{1}{\Sigma_t}\ln(1-\xi) \quad (5.3)$$

And as (1- ξ) is distributed in the same way than ξ then the first one is replaced.

In MCNP the distance to next collision is sampled as Eq. (5.3) and the neutron is moved there.

Then, the material that will interact is sampled, as well as the reaction (absorption, scattering…), and the generation of secondary particle (type, weight, energy, flight direction…). The neutron is tracked until it is absorbed or it leaks the geometry. Then a new neutron is "born" and the process is repeated until all histories are made and the average results are shown.

Many different processes occur during the simulation and the user needs to introduce in the input file which results want to be printed after it. Some general results are printed by default unless it is especially asked to avoid them. For the rest of results tallies are used to require some events happened during the simulation, such as the number of particles that have crossed a surface, the number of particle paths in a cell, the number of certain collisions, etc. After all the histories the tally results are given together with statistical parameters about them.

Each neutron has a weight set when born. When the neutron is absorbed, it can be treated in two different ways. Analog absorption treats the neutron as a particle and thus when it is absorbed the particle disappears or, what is the same, loses all its weight. In implicit absorption, the neutron weight Wn is reduced as shown in Eq. (5.4).

$$W_n = \left(1 - \frac{\sigma_a}{\sigma_t}\right) * W_n \qquad (5.4)$$

σ_a/σ_t is the absorption microscopic cross-section over the total microscopic cross-section.

For instance, if the user wants to make a tally quite far from the neutron source, in analog absorption when neutrons arrive to this zone and get absorbed they disappear. In implicit absorption, if they still have enough weight when they arrive to the tally zone, they can interact once (losing some weight) and interact again, contributing twice to the tally with the same neutron.

The tally used to estimate the TBR is the flux averaged over a cell, in particles/cm2 (mnemonic F4 for MCNP users). It is the sum of the weight times the length of all particle tracks in a cell divided by the cell volume. If the tally is modified with the FMn card, it is possible to calculate something with the form C*integral(flux(E)*Rm(E)). C is defined as the density of Li-6 (the tritium breeding material) and Rm(E) as 105, which is an extense table with the microscopic cross section for reaction $^{6}Li(n,t)4He$. Each time a neutron undergoes this reaction in Li-6, it is tracked multiplied by the cross-section at the energy of the neutron. Finally, when all the histories are done, MCNP gives the results per source particle. If the volume of the cells where there is lithium is set to 1 the tally is directly the TBR.

6. Calculations

After having defined the problem the results will be detailed in this section. A Monte Carlo computational method, MCNP-5 (Monte Carlo N-Particle) [X-5 Monte Carlo Team, 2005], has been used for TBR calculations at KIT in order to quantify its reduction when a distributed antenna is added in the blanket. FENDL-2.1 [IAEA, 2004] is the nuclear data library used. The results given here are separated into two groups; the final configuration and a parametric analysis about it.

Results in tables are usually structured into 3 columns. The first one, called "without antenna", refers to the original configuration where the antenna is not implemented. The second one, called "with antenna", refers to the configuration where the antenna has been implemented. The third one, called "variation", is the percentage increase of the second column respect the first one. If not indicated, the results are given in neutrons/neutron_source_particle.

If possible, the results will be given with their error. They will appear as a pair of numbers where the result is the one at left and the error at right. The error is always as a percentage of the result. Total capture has not an error associated. That is because every capture tally has a material associated. As long as the total capture includes all parts of the tokamak, with their respective materials, the error increases a lot due to its accumulative property. Nevertheless, it is added because in some cases it gives information about the neutrons behavior.

6.1. Final configuration

To sum up previous chapters, the final configuration studied is a 11.25º DEMO tokamak corresponding to 1 inboard and 1.5 outboard blanket segment, where each segment has 6 modules (12 modules in a poloidal-radial cross-section). FW, blanket, manifold, vacuum vessel, upper port, equatorial port, down port, divertor and the plasma are the tokamak elements included in the geometry. The blanket concept used is the Helium Cooled Pebble Bed, which was explained in Chapter 5.2. The antenna used was detailed in Chapter 5.1.

MCNP most important results on this configuration are shown in Tab. 6.1.

	Without antenna	With antenna	Variation (%)
Breeding volume per 11.25° torus (m^3)	23,890	23,638	-1,055%
Net multiplication	1,613 0.0001	1,609 0.0001	-0,248%
Total capture	1.610	1,605	-0,311%
Capture in breeding material	1,321 0.0003	1,316 0.0003	-0,379%
Tritium Breeding Ratio	1,145 0.0003	1,141 0.0003	-0,349%

Table 6.1 Main MCNP results for the Final ICRH antenna Configuration

The breeding volume used is an important parameter because it indicates the volume that is not anymore available for tritium production. Despite the large surface used for the antenna (62 m^2 in the whole reactor) the reduction of breeding volume is rather small (1.055%).

The net multiplication and the total capture indicate the behavior of the neutron analysis and helps to compare with other models. Their values should be similar if the tritium self-sufficiency is sought. In this case both of them are decreased (-0.248% and -0.311% respectively) mainly because some breeding material is removed, which is where the neutron multiplication occurs and it is more absorbing than the antenna.

The capture in breeding material is, indeed, lower because it only considers part of the total tokamak, but it is the part where the breeding material is placed and thus should (and is) similar to the TBR in terms of variation. It is reduced -0.379%.

Finally, the Tritium Breeding Ratio is the most important parameter because it is the aim of this work. When adding the antenna, the TBR remains still very high with a value of 1.141, which still largely guarantees the tritium self-sufficiency. With a variation value of -0.349%, the antenna presents a very low effect on the TBR.

In order to better understand the results, neutron absorptions in the different parts of the module where the antenna is placed are shown in Tab. 6.2 and neutron absorptions in the different parts of the whole tokamak modeled are shown in Tab. 6.3.

	Without antenna	With antenna	Variation (%)
FW (W first layer)	4,016E-03 0.0017	3,501E-03 0.0018	-12,824%
Blanket breeder	1,829E-01 0.0008	1,777E-01 0.0008	-2,843%
Side walls	2,846E-03 0.0023	3,135E-03 0.0022	10,155%
FW (Steel second layer)	7,311E-03 0.0009	6,300E-03 0.0009	-13,833%
Straps (antenna)	-	2,405E-03 0.0017	-

Table 6.2 MCNP results: neutron absorptions in the whole module 4 for the Final ICRH antenna Configuration

When adding the antenna to the model, only some FW and breeding blanket is removed. It can be seen in Tab. 6.2 how these parts get the neutron absorption reduced (-12.824% in the case of tungsten-FW, -13.833% in the case of steel-FW and -2.843% in the case of blanket breeder). In the case of side walls, in the other hand, absorption is increased (10.155%). The explanation is that the antenna is centered in the module and does not use all the space, and therefore the side walls remain intact and keep the same volume. The antenna absorption is lower than the breeding blanket absorption and the result is a higher neutron profile, which leads to a higher absorption behind the antenna.

	Without antenna	With antenna	Variation (%)
FW (W first layer)	3,239E-02 0.0008	3,196E-02 0.0008	-1,328%
Blanket breeder	1,321E+00 0.0003	1,316E+00 0.0003	-0,379%
Side Walls	2,301E-02 0.0009	2,320E-02 0.0008	0,826%
FW (Steel second layer)	5,432E-02 0.0004	5,329E-02 0.0004	-1,896%
Blanket backplates and manifold	1,459E-02 0.0021	1,473E-02 0.0021	0,960%
Vacuum Vessel	1,021E-02 0.0028	1,027E-02 0.0028	0,588%

Table 6.3 MCNP results: neutron absorption in the whole tokamak modeled in Final Configuration

When all the model is studied, the effect on the parts of Tab. 6.2 is now smoothed to lower values, because the effect in other modules where there is no antenna is much lower. Again, the parts which have no volume removed increase their absorption (Side Walls, backplates, manifolds and Vacuum Vessel). To illustrate this effect, the neutron profile is shown in Fig. 6.1 (and its error in Fig. 6.2).

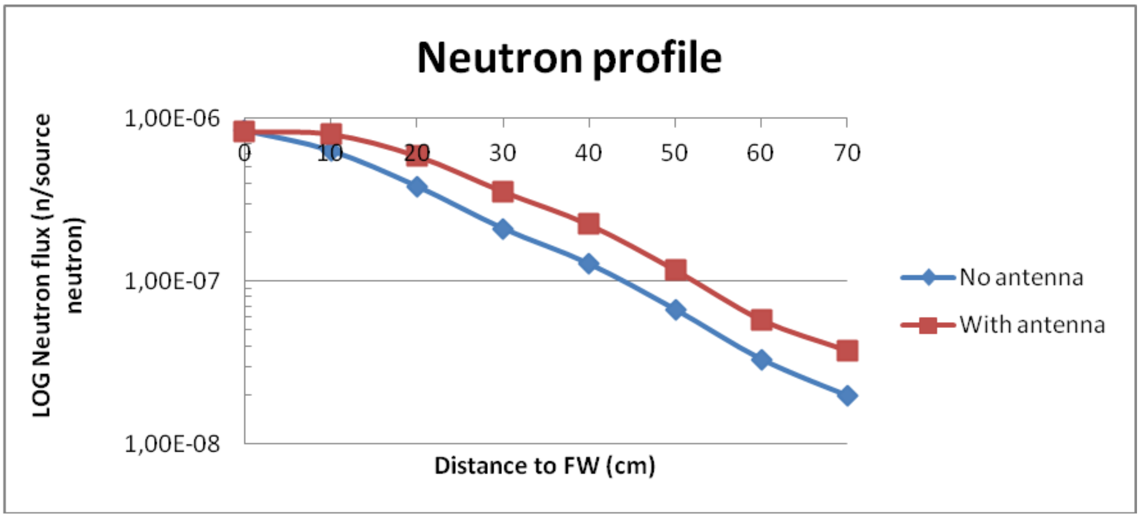


Figure 6.1 Neutron flux profile throughout the blanket with and without the antenna in Final Configuration

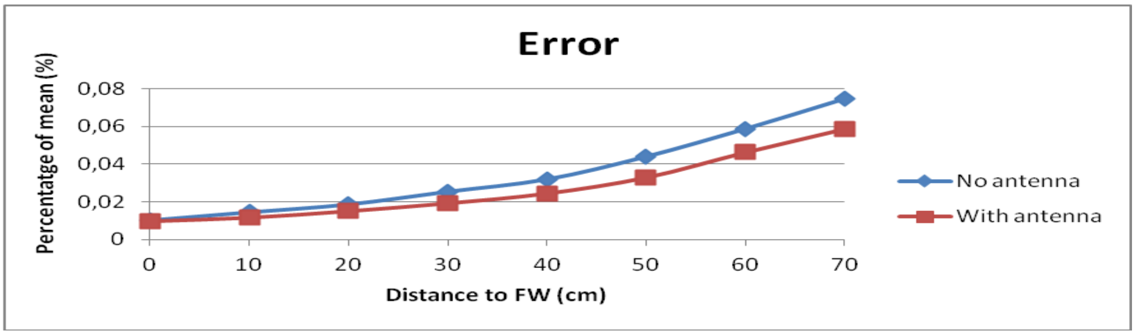
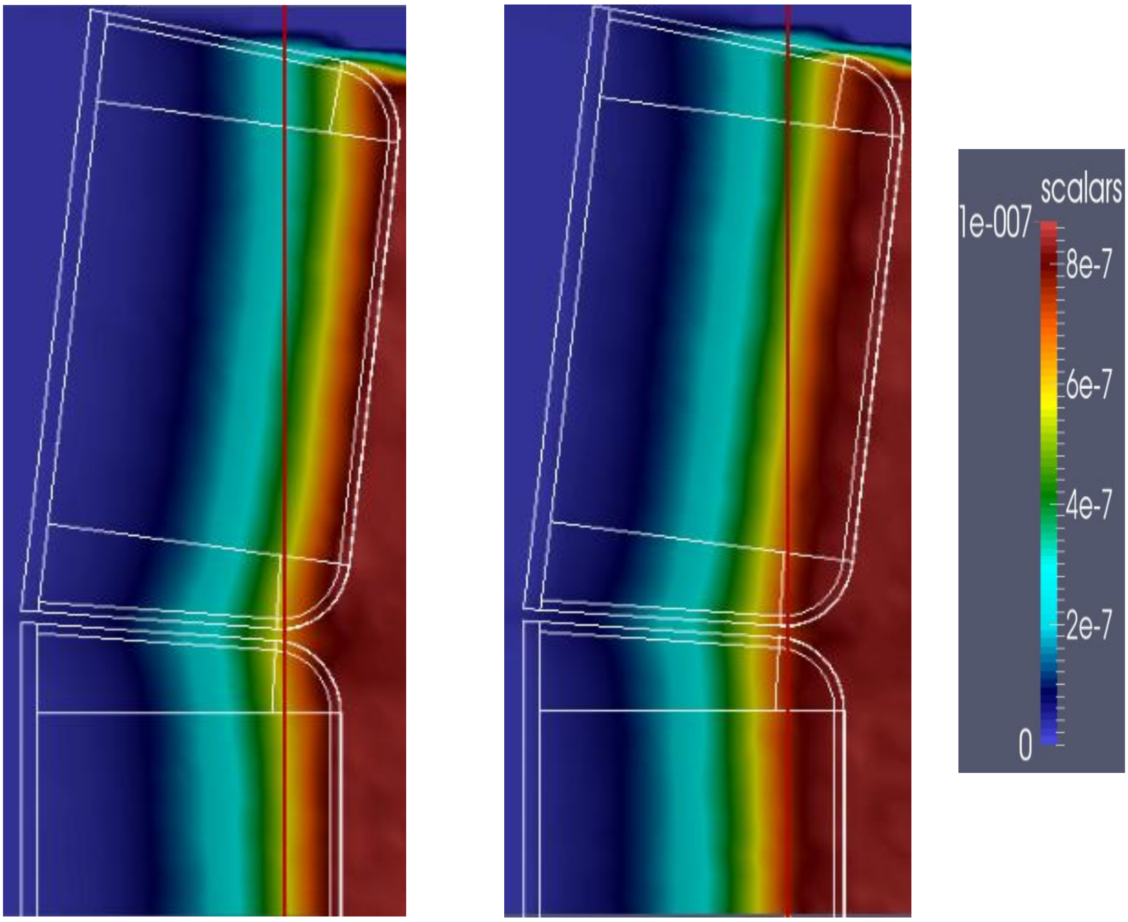


Figure 6.2 Error for Fig. 6.1

Neutron flux profiles are calculated with a superimposed mesh (FMESH tally) creating cubes 5-cm edged. The relatively thin mesh ends up with rather small cubic cells. The further from the plasma chamber, the lower the value of the tally is, and the larger is the statistical error. The errors at the end of the blanket are too big to study that zone in detail and therefore no conclusions can be extracted there. This could be solved using variance reduction techniques but as the important here is to understand the neutron flux behavior the antenna leads to and the antenna is placed near the plasma chamber, it is not necessary.

From Fig. 6.1 the effect mentioned above can be seen. The flux at the antenna decreases slowly until it reaches the breeding zone, where it decreases significantly. This effect leads to a displacement back of the neutron flux and then the flux is locally bigger everywhere after the antenna. This is important because a bigger flux leads to a bigger absorption, which at the same time leads to a bigger TBR (locally). In the end TBR in the case with antenna will be lower anyway because the first part of the area under the curve is not contributing to produce tritium, but the effect of a bigger flux behind the antenna smoothes the loss of TBR as much as deep the blanket is. That is why a reduction of breeding volume of -1.055% leads only to a -0.349% reduction on the TBR.

When using FMESH tally, a special output file is created by MCNP. It is called MESHTAL by default, and it is the neutron flux calculated in all the mesh elements. Using [Paraview] visualization software this file can be plotted in 3D. In Fig. 6.3 this 3D plot has been cut in a 2D slice and superposed to the CAD blanket geometry, and then the effect of a displacement back of the neutron flux can be clearly seen.



(a) Without antenna (b) With antenna (c) Legend

Figure 6.3 Effect of the antenna in the neutron flux profile across the blanket

In conclusion, the effect of the antenna on the TBR is really low with a loss of -0.349%. One should notice that it is very low despite the large surface of FW used (62m^2 in the whole tokamak). A good comparison for these results could be the comparison against a void opening in the equatorial port, which is required for other auxiliary heating systems such as Neutral Beam (NB). Taking 16 ports with 1 m x 2 m openings (32 m^2 in total) the loss of TBR is around 10% in a HCPB blanket [Fischer, 2015]. Then the effect of the complete ICRF antenna in the whole tokamak, which uses 62 m^2 of surface, is equivalent to a single void opening of 1.40 m^2 in the equatorial port, which is less than a single port.

Furthermore, the antenna does not need to be placed in a port, so it can leave that space for other auxiliary heating methods or diagnostic devices and work complementary.

6.2. Parametric analysis

DEMO is still in a preliminary phase and therefore it is still under development. ITER will be the key milestone bringing the opportunity to test and improve many features, but that also means that there is still a wide range of possibilities concerning different aspects. The results so far have shown that the antenna concept is feasible in terms of tritium self-sufficiency in the current configuration. It is important to make a parametric analysis to see how the loss of TBR changes due to the antenna if some of the parameters are biased.

The parameters studied here are a compromise between an apparently strong dependence with the TBR in one hand, and the ones which are more likely to change in a near future in the other hand. The objective, then, is to make this work more flexible and let the reader still estimate the loss of TBR in a short and middle term horizon.

The first parameter studied is the type of breeding blanket, including the already studied in the final configuration, the Helium Cooled Pebble Bed (HCPB), and extending it to the other two liquid concepts that are currently being considered for DEMO, the Helium Cooled Lithium Lead (HCLL) and the Water Cooled Lithium Lead (WCLL). All of them were explained in Chapter 5.2.

The second one is the covering ratio of the straps. It is defined as the projected surface of the straps respect the total projected surface of the antenna. Complementing the 0.72 covering ratio of the final configuration, two more point calculations at 0.49 and 0.94 are made.

The third one is the depth of the antenna, and its effect relies mainly in the fact that it is directly related with the breeding volume removed. Complementing the 20 cm depth of the final configuration, another very conservative 40 cm depth is made.

The forth one is the thickness of the straps. The final configuration uses straps made of Eurofer 2 cm thick, and it is complemented by the same type of strap but 4 cm thick and a different strap with the composition of the FW; 2.5 cm Eurofer with a first layer of 0.2 cm of tungsten.

Finally, the fifth parameter is the poloidal position. The final configuration have the antenna located at the 4th poloidal outboard module. This is complemented with two more, having the antenna located at the 3rd module (equatorial module) and the 6th one (upper module). These are the worst and the best case, respectively, of this parameter.

6.2.1. Blanket concept: HCPB, HCLL and WCLL

Three different blanket concepts are being considered in the framework of the European Power Plant Physics and Technology (PPPT) program [Pereslavtsev, 2014a] for DEMO. The already studied Helium Cooled Pebble Bed (HCPB) with lithium ceramics pebbles (Li4SiO4) as tritium breeder and beryllium as neutron multiplier, and the Helium Cooled Lithium Lead (HCLL) and Water Cooled Lithium Lead (WCLL) both with the Pb-Li eutectic alloy acting as tritium breeder and neutron multiplier. They are assumed to be used in DEMO regardless the plasma physics parameters and dimensions, so a generic reactor model is used as a common basis for the development and evaluation of these blanket concepts.

In 5.2 an explanation of all these blanket concepts was done so only the results are shown in this section. In Annex X the composition of the three concepts in all the parts of the reactor is detailed. The results regarding the HCLL blanket concept are shown in Fig. 6.4 and the ones regarding the WCLL blanket concept are shown in Fig. 6.5. However, the most important in the present work is the comparison between them. Those results are shown in Fig. 6.6.

	Without antenna	With antenna	Variation (%)
Breeding volume per 11.25° torus (m^3)	23,890	23,638	-1,055%
Net multiplication	1,606 0.0001	1,603 0.0001	-0,187%
Total capture	1,596	1,594	-0,125%
Capture in breeding material	1,193 0.0003	1,187 0.0003	-0,503%
Tritium Breeding Ratio	1,128 0.0003	1,122 0.0003	-0,532%

Table 6.4 MCNP results for HCLL blanket concept

Obviously the breeding volume used is the same than for the HCPB blanket concept, because only the breeding homogeneous material was changed. The rest of values are quite lower with HCLL than they were with HCPB. For instance, the TBR without antenna is 1.128 and in the final configuration it was 1.145. Beryllium is the superior neutron multiplier with the highest neutron multiplication power, and its low atomic number makes it also a good moderator. That results in a high multiplication and a high moderation, which combined with the very high lithium cross-section at low energies to produce tritium allows a higher TBR.

	Without antenna	With antenna	Variation (%)
Breeding volume per 11.25° torus (m3)	23,890	23,638	-1,055%
Net multiplication	1,529 0.0004	1,526 0.0004	-0,196%
Total capture	1,527	1,524	-0,196%
Capture in breeding material	1,110 0.001	1,104 0.001	-0,541%
Tritium Breeding Ratio	1,005 0.001	1,000 0.001	-0,507%

Table 6.5 Main MCNP results for WCLL blanket concept

The results for the WCLL blanket concept are rather low compared with the HCPB or the HCLL concepts. In current PPPT design studies the WCLL concept presents a higher TBR, but in this work the WCLL breeding blanket has filled a HCPB model to simplify the work. The most interesting parameter, for this thesis, is the variation when introducing the antenna, and that is rather independent of the absolute values.

Furthermore, HCLL is composed by 85% Pb-Li + 8% Eurofer + 7% void, while WCLL is composed by 80% Pb-Li + 18% Eurofer + 2% Water. Water is a very good moderator and therefore this blanket concept should have a higher TBR taking into account the very high cross-section of Li at low energies for the reaction producing tritium. Nevertheless, its much higher presence of Eurofer, which produces no tritium useful reactions, and lower Pb-Li, which leads to lower net multiplication and TBR, can compensate the better moderator properties, which with the very low water fraction are very significant.

	HCPB	HCLL	WCLL
Breeding volume per 11.25° torus (m3)	-1,055%	-1,055%	-1,055%
Net multiplication	-0,248%	-0,187%	-0,196%
Total capture	-0,311%	-0,125%	-0,196%
Capture in breeding material	-0,379%	-0,503%	-0,541%
Tritium Breeding Ratio	-0,349%	-0,532%	-0,507%

Table 6.6 Comparison of MCNP results for HCPB, HCLL and WCLL blanket concepts

But the aim of this work is not to improve the blanket concepts or study its feasibility, but to study the effect of the antenna on the TBR. For that, Tab. 6.6 must be studied to see not the TBR values but the loss of TBR for the different blankets.

The HCPB is the best option, with the current design, in terms of tritium sufficiency with a loss of -0.349% and HCLL is the worst option with a value of -0.532%. WCLL stays in the middle with a value of -0.507%. It has been explained why HCPB has the highest TBR, but for the loss of TBR the key parameter is lead. This element has a rather high elastic-scattering cross-section and, combined with being a heavy element (and thus a bad moderator) it results in a high reflective material for neutrons, which leads to increase the parasitic absorption at the straps of the antenna and thus increases the loss of TBR. The effect is higher in HCLL than in WCLL because the highest moderation power of water alleviates the behavior.

The neutron flux profile throughout the blanket (in the case without antenna) for all three blanket concepts is shown in Fig. 6.4, with its error in Fig. 6.5, and it can be clearly seen the bigger flux for HCLL and WCLL, due to the their higher reflectivity, and how WCLL is lower than HCLL due to water.

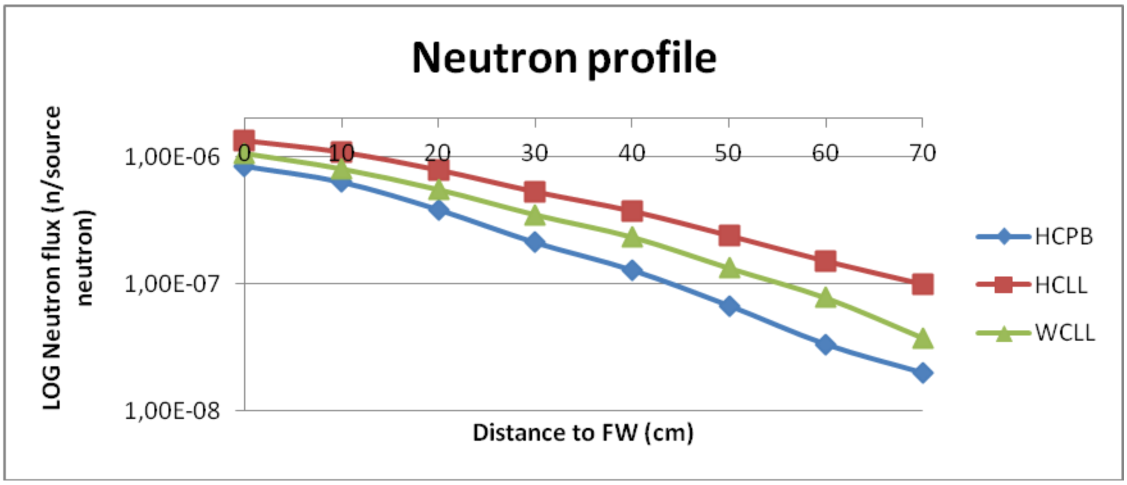


Figure 6.4 Neutron flux profile throughout the blanket without antenna for different blanket concepts

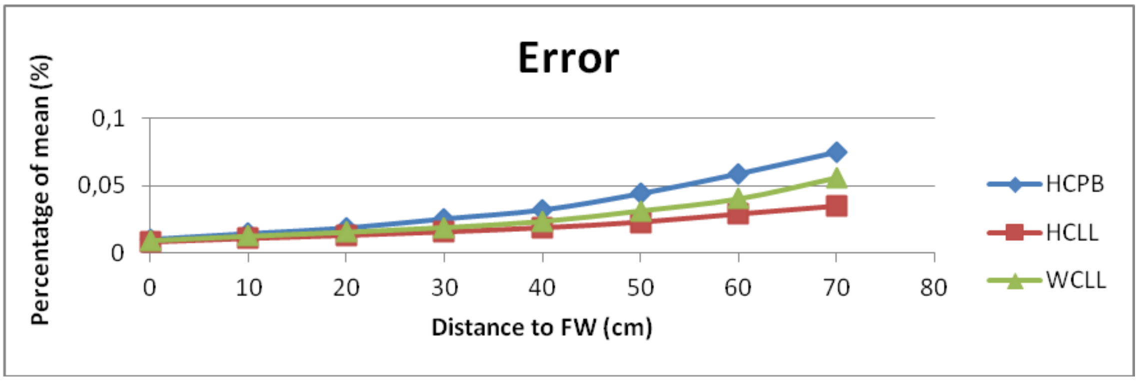


Figure 6.5 Error for Fig. 6.4

6.2.2. Covering ratio

The covering ratio of the straps is the ratio between the projected surface of the straps and the total projected surface of the antenna. It goes from 0, one-dimensional straps with zero thickness, to 1, a continuous 360º toroidally strap. Both endpoints are purely theoretical and useless to study (the second case can't fit the blanket modularity). Fig. 6.6 may help to illustrate this concept.

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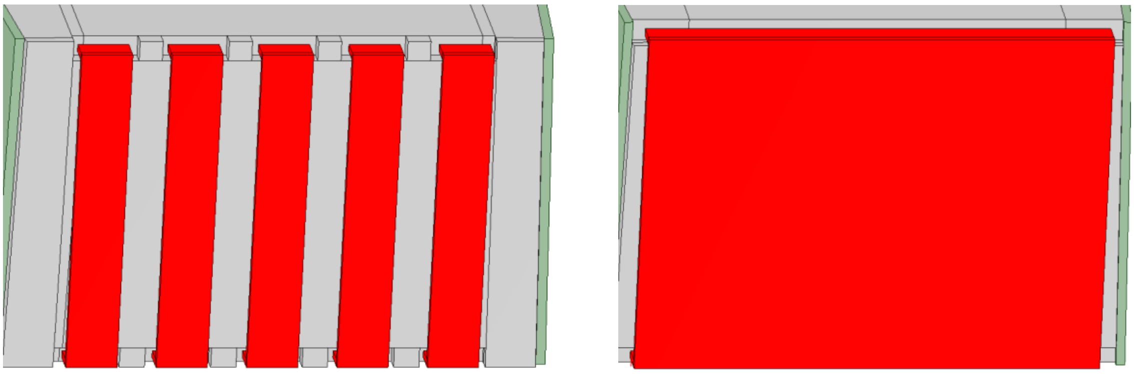


(a) Covering ratio 0.49 **(b) Covering ratio 0.94**

Figure 6.6 Antenna illustrated at different covering ratios (0.49 and 0.94)

Complementing the final configuration, which have a covering ratio of 0.72, two more point calculations are done at 0.49 and 0.94. The final covering ratio that will be used in DEMO is not defined but it will very likely be in the middle. The 0.94 covering ratio is the biggest one which still fits the blanket modularity and the antenna restriction of having the Faraday shield flush with the FW.

The results of the simulation for these two covering ratio are shown in Tab. 6.7 and Tab. 6.8 respectively. In Tab. 6.9 the comparison between them and the final configuration is shown.

In Tab. 6.7 and Tab. 6.8 the first column of results is identical because the configuration without antenna is the same for both, but when adding the antenna (second column), the values are lower for the higher covering ratio. These two tables should be studied to better understand the results, but Tab. 6.9 is more useful to check the comparative results.

	Without antenna	With antenna	Variation (%)
Breeding volume per 11.25° torus (m^3)	23,890	23,641	-1,042%
Net multiplication	1,613 0.0001	1,611 0.0001	-0,105%
Total capture	1,610	1,608	-0,124%
Capture in breeding material	1,321 0.0003	1,318 0.0003	-0,227%
Tritium Breeding Ratio	1,145 0.0003	1,143 0.0003	-0,175%

Table 6.7 MCNP results for a covering ratio of 0.49

	Without antenna	With antenna	Variation (%)
Breeding volume per 11.25° torus (m^3)	23,890	23,637	-1,059%
Net multiplication	1,613 0.0001	1,608 0.0001	-0,291%
Total capture	1,610	1,605	-0,311%
Capture in breeding material	1,321 0.0003	1,314 0.0003	-0,530%
Tritium Breeding Ratio	1,145 0.0003	1,140 0.0003	-0,437%

Table 6.8 MCNP results for a covering ratio of 0.94

	0.49	0.72	0.94
Breeding volume per 11.25° torus	-1,042%	-1,055%	-1,059%
Net multiplication	-0,105%	-0,248%	-0,291%
Total capture	-0,124%	-0,311%	-0,311%
Capture in breeding material	-0,227%	-0,379%	-0,530%
Tritium Breeding Ratio	-0,175%	-0,349%	-0,437%

Table 6.9 Comparison of MCNP results for all different covering ratios (0.49, 0.72 and 0.94)

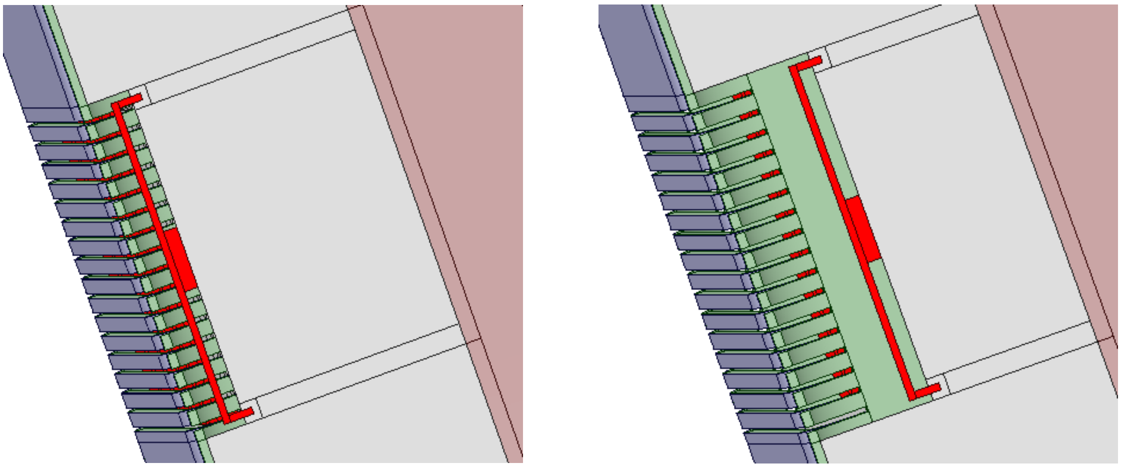
A bigger covering ratio results in a bigger parasitic absorption of neutrons in the antenna. Those neutrons are lost and thus not useful anymore for breeding tritium. For a covering ratio of 0.49, a loss of TBR of -0.175% results. For the final configuration a loss of -0.349% is achieved, as was shown in Chapter 6.1, and finally for a covering ratio of 0.94 a higher -0.437% occurs.

As expected, the worst case is the covering ratio of 0.94 because it is the biggest covering ratio achievable. Even then, the loss of TBR is really low.

6.2.3. Antenna depth

The depth of the antenna is the total depth of breeding blanket that the device uses. It is directly related to the breeding volume removed and therefore is very likely to strongly affect the TBR. Not all the depth is removed from breeding blanket because there are the capacitor holes in the upper and lower part of the strap which are 5 cm more deep than the rest. In Fig. 6.7 this can be seen (in both cases).

The final configuration of the antenna is 20 cm deep and that calculation is complemented with another 40 cm deep case. It is a very conservative case, because the depth of the antenna is not very likely to be changed. Taking into account the very low value of the antenna effect on the TBR, a low change in the depth would result in a very low change in this effect. Instead, this very conservative case helps to understand the effect of the depth and acts, at the same time, as the worst reasonably case. In Fig. 6.7 both 20 cm and 40 cm can be seen.



(a) Antenna 20 cm deep **(b) Antenna 40 cm deep**

Figure 6.7 Antenna illustrated at different depths used (20 cm and 40 cm)

In Tab. 6.10 the results of the simulation with the antenna 40 cm deep are shown. The comparison with the final configuration of the antenna is shown in Tab. 6.11.

	Without antenna	With antenna	Variation (%)
Breeding volume per 11.25° torus (m^3)	23,890	23,217	-2,817%
Net multiplication	1,613 0.0001	1,608 0.0001	-0,310%
Total capture	1,610	1,605	-0,311%
Capture in breeding material	1,321 0.0003	1,312 0.0003	-0,681%
Tritium Breeding Ratio	1,145 0.0003	1,139 0.0003	-0,524%

Figure 6.10 MCNP results for an antenna depth of 40 cm

	20 cm	40 cm
Breeding volume per 11.25° torus	-1,055%	-2,817%
Net multiplication	-0,248%	-0,310%
Total capture	-0,311%	-0,311%
Capture in breeding material	-0,379%	-0,681%
Tritium Breeding Ratio	-0,349%	-0,524%

Table 6.11 Comparison of MCNP results for different antenna depths (20 cm and 40 cm)

As expected, the bigger reduction on the breeding volume deals with a bigger reduction on the rest of parameters. Despite the reduction of breeding volume is significantly different (2.82% instead of 1.06%) the reduction on the loss of TBR is only quite bigger (0.52% instead of 0.35%). The explanation can be illustrated with the neutron fluxes across the blanket, shown in Fig. 6.8 (and errors in Fig. 6.9.). Even in the very conservative case of a 40 cm deep antenna, the loss of TBR stays in a very low value of -0.524%.

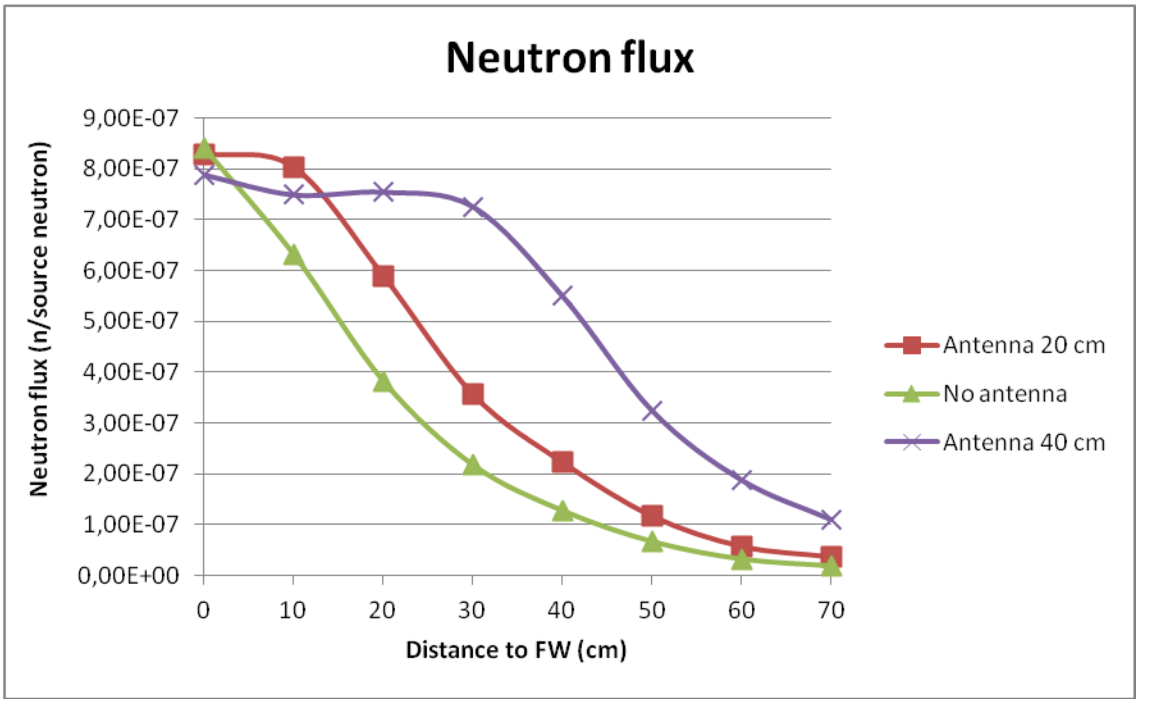


Figure 6.8 Comparison of neutron flux throughout the blanket between the case without antenna and the cases with different depths (20 cm and 40 cm)

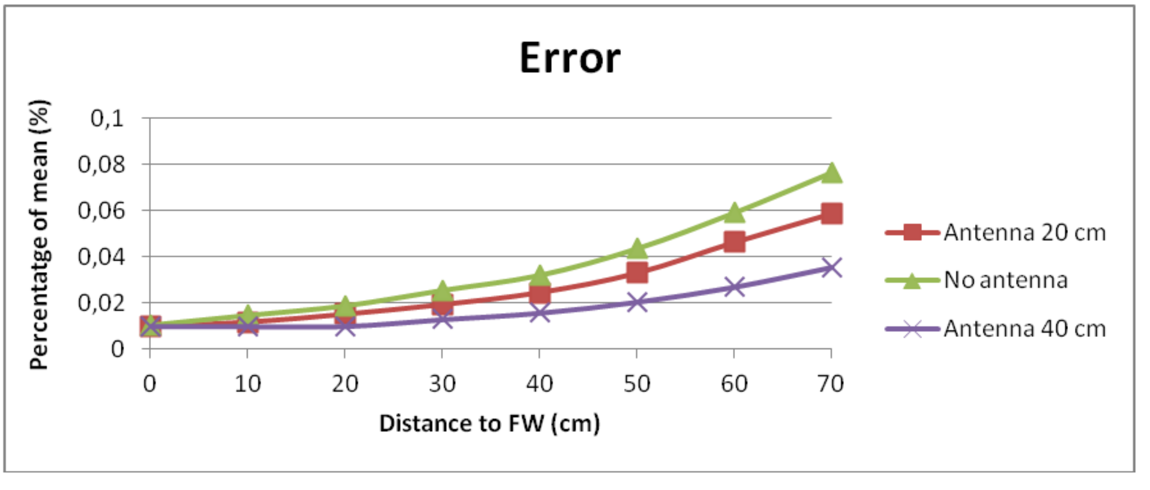


Figure 6.9 Error for Fig. 6.8

The antenna is mainly void space and some steel. When some breeding zone, which is highly absorber, is removed, the absorption in that region strongly decreases. In Fig. 6.8 it can be seen how the fluxes, which are strongly related to absorption, do not start decreasing until they reach the breeding zone. As explained in the beginning of this section, that happens 5 cm before the end of the antenna.

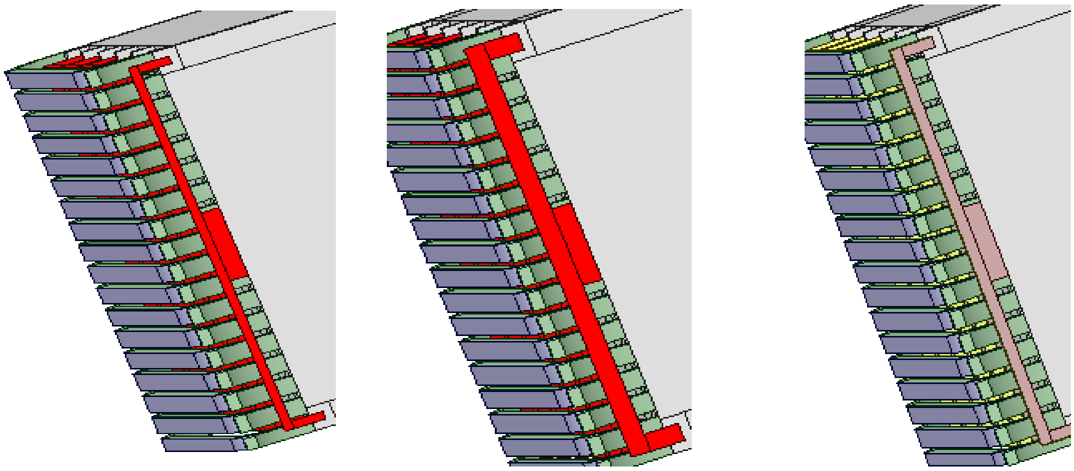
In all this depth until the breeding zone is reached there is not a contribution on the TBR, but when this zone is reached, the flux is bigger, locally, for the case with antenna. Then the absorption is bigger, locally, in that case, and this will occur in all the depth until the end of the breeding zone. The conclusion is that the more deep the blanket, the more smoothed the effect of the antenna on the TBR is. That is the explanation why with a strong increase of breeding volume removed from one antenna to the other one (from -1.055% to -2.817%) the loss of TBR only increases a little bit (from -0.349% to -0.524%).

Another interesting thing can be extracted from Fig. 6.8. The neutron flux at the beginning of the blanket is quite lower with an antenna 40 cm deep than with an antenna 20 cm deep or without antenna. That is because an important part of the neutron flux comes from the reflected neutrons due to elastic scattering in the breeding zone. In the 40 cm case the breeding zone is smaller and it is located further, which results in a lower neutron flux in the zone.

6.2.4. Straps thickness

The thickness of the straps is not likely to change too much but until the functionality of the antenna will be fully defined it can't be assured. This parameter is directly related with the parasitic absorption of neutrons because it varies the amount of material between the plasma and the breeding blanket which do not contribute to the TBR.

The final configuration of the antenna uses straps 2 cm thick and this case is complemented with two more. The first one, following the same idea than in the case with the antenna depth when a very conservative case was taken, a 4 cm thick straps is implemented. This case will allow to understand the effect of the thickness on the TBR because it is the only parameter changed. The second one, however, uses a strap with the composition of the FW. That is, 2.5 cm Eurofer plus 0.2 cm Tungsten, which will likely be the worst case regarding the straps thickness. All cases can be seen in Fig. 6.10.



(a) Antenna with 2 cm straps thickness

(b) Antenna with 4 cm straps thickness

(c) Antenna with 2.5 cm Eurofer + 0.2 cm W straps thickness

Figure 6.10 Antenna illustrated at different straps thickness

The results of the simulation for the first case, 4 cm thick, are shown in Tab. 6.12. The results for the second case, 2.5 cm Eurofer + 0.2 cm Tungsten, are shown in Tab. 6.13, and a comparison of the final configuration and these two is shown in Tab. 6.14.

As in previous sections, the results for different cases are shown in case the reader requires more details, but the discussion will be about Tab. 6.14 which summarizes the other two.

	Without antenna	**With antenna**	**Variation (%)**
Breeding volume per 11.25° torus (m^3)	23,890	23,635	-1,067%
Net multiplication	1,613 0.0001	1,607 0.0001	-0,372%
Total capture	1,610	1,604	-0,373%
Capture in breeding material	1,321 0.0003	1,311 0.0003	-0,757%
Tritium Breeding Ratio	1,145 0.0003	1,138 0.0003	-0,611%

Table 6.12 MCNP results for an antenna with 4 cm straps thickness

	Without antenna	**With antenna**	**Variation (%)**
Breeding volume per 11.25° torus (m^3)	23,890	23,636	-1,063%
Net multiplication	1,613 0.0001	1,609 0.0001	-0,248%
Total capture	1,610	1,606	-0,248%
Capture in breeding material	1,321 0.0003	1,314 0.0003	-0,530%
Tritium Breeding Ratio	1,145 0.0003	1,140 0.0003	-0,437%

Table 6.13 MCNP results for an antenna with 2.5 cm Eurofer + 0.2 cm W straps thickness

	2 cm	2.5 + 0.2 cm	4 cm
Breeding volume per 11.25° torus	-1,055%	-1,063%	-1,067%
Net multiplication	-0,248%	-0,248%	-0,372%
Capture in breeding material	-0,379%	-0,530%	-0,757%
Tritium Breeding Ratio	-0,349%	-0,437%	-0,611%

Table 6.14 Comparison of MCNP results for different straps thickness (2 cm, 2.5 + 0.2 cm and 4 cm)

As expected, the more thick the strap is, the more the loss of TBR. In the final configuration the loss is -0.349% and it raises up to -0.611% when the thickness is doubled. In the case with a composition like the FW and a thickness between the first two, the loss is in the middle with a value of -0.437%.

The neutron fluxes across the blanket for all cases are shown in Fig. 6.11 (and the error in Fig. 6.12). Like the absorption, the flux is lower when the strap is more thick, because the parasitic absorption in the straps decrease the total amount of neutrons available for breeding tritium.

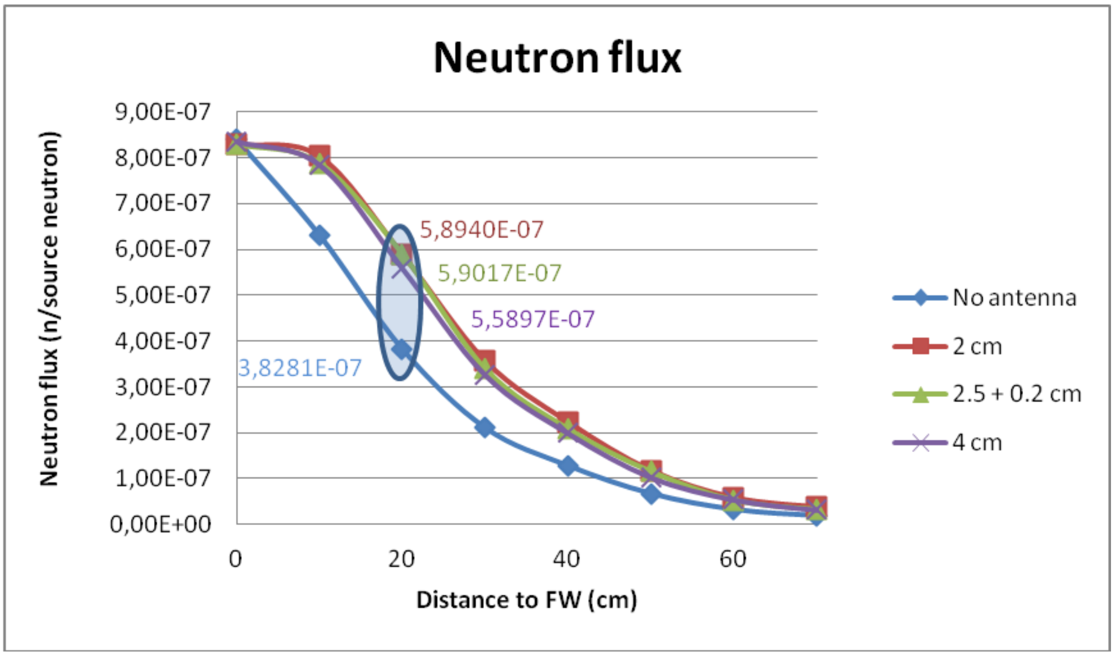


Figure 6.11 Comparison of neutron flux throughout the blanket between the case without antenna and the cases with different straps thicknesses (2 cm, 4 cm and 2.5 + 0.2 cm)

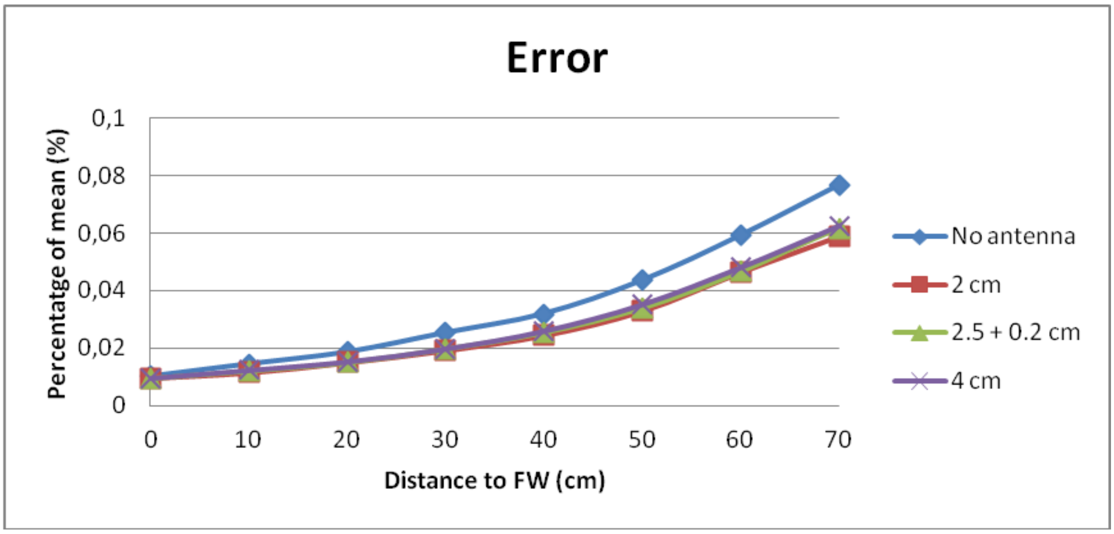


Figure 6.12 Error of Fig. 6.11

6.2.5. Poloidal position

The last parameter studied is the poloidal position of the antenna in a radial-poloidal cross section of the torus (see Fig. 6.13). The final position will be defined by the functionality of the antenna and it is still being studied. Anyway, it is already set that it will be placed in the outboard upper modules, so modules 3, 4, 5 and 6 are the candidates. The final configuration has the antenna placed in module 4.

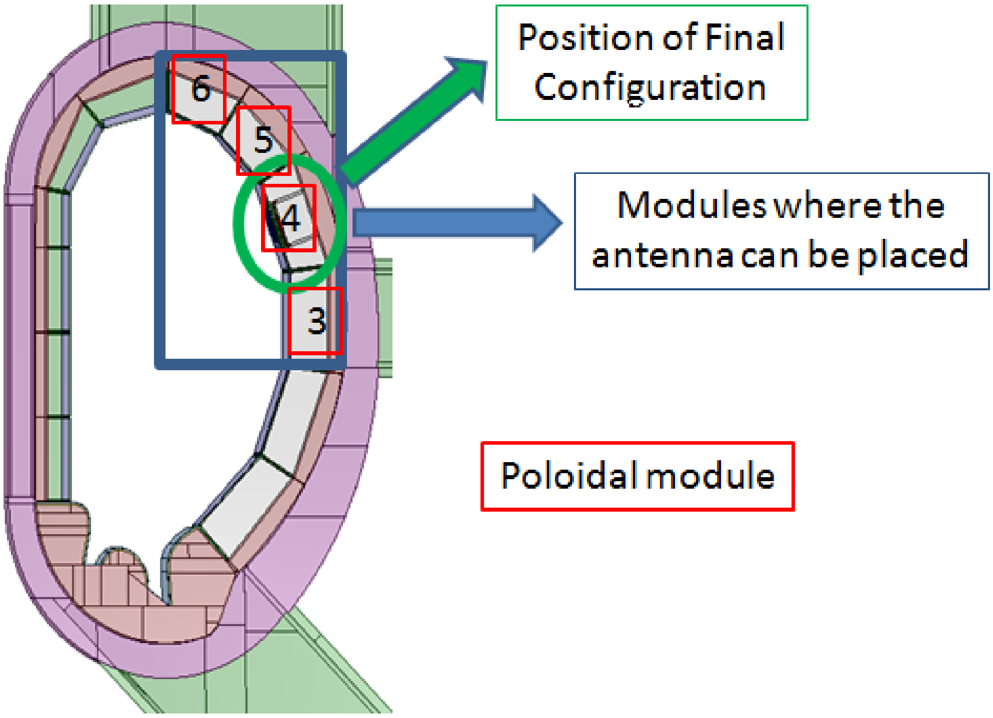


Figure 6.13 Poloidal position possibilities to place the antenna

The effect on the loss of TBR of this parameter is directly related to the Neutron Wall Loading (NWL) because it is an indicator of the amount of neutrons in the region on which the antenna will have an impact, and thus the more NWL, the more loss of TBR there will be. Hence, and as can be seen in Fig. 6.14, module 3 is the worst case in terms of TBR, which corresponds to 0º (or 360º), and module 6 is the best, which corresponds to 90º. Both cases have been studied to complement the final configuration, which placed the antenna in module 4, corresponding to 40º.

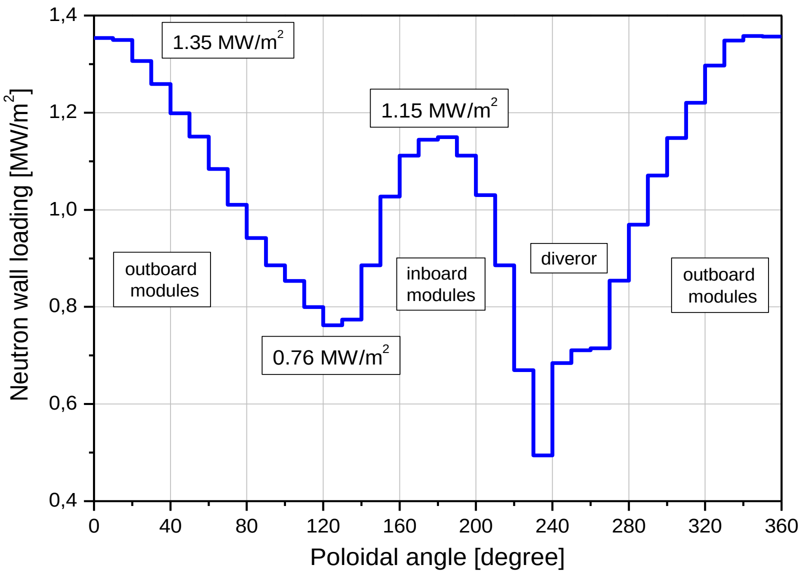


Figure 6.14 Neutron Wall Loading (NWL) in HCPB DEMO reactor [Pereslavtsev, 2014b]

Results in case of module 6 are shown in Tab. 6.15 and results in case of module 3 are shown in Tab. 6.16. A comparison between these two and final configuration can be found in Tab. 6.17.

	Without antenna	**With antenna**	**Variation (%)**
Breeding volume per 11.25° torus (m^3)	23,890	23,687	-0,850%
Net multiplication	1,613 0.0001	1,611 0.0001	-0,124%
Total capture	1,610	1,607	-0,186%
Capture in breeding material	1,321 0.0003	1,317 0.0003	-0,303%
Tritium Breeding Ratio	1,145 0.0003	1,143 0.0003	-0,175%

Table 6.15 MCNP results for an antenna with placed in module 6

	Without antenna	With antenna	Variation (%)
Breeding volume per 11.25° torus (m^3)	23,890	23.630	-0,850%
Net multiplication	1,613 0.0001	1,609 0.0001	-0,248%
Total capture	1,610	1,606	-0,248%
Capture in breeding material	1,321 0.0003	1,316 0.0003	-0,379%
Tritium Breeding Ratio	1,145 0.0003	1,141 0.0003	-0,349%

Table 6.16 MCNP results for an antenna with placed in module 3

	Module 3	Module 4	Module 6
Breeding volume per 11.25° torus	-1,088%	-1,055%	-0,850%
Net multiplication	-0,248%	-0,248%	-0,124%
Capture in breeding material	-0,379%	-0,379%	-0,303%
Tritium Breeding Ratio	-0,349%	-0,349%	-0,175%

Table 6.17 Comparison of MCNP results for different polodial positions (modules 3, 4 and 6)

From the available modules for placing the antenna, shown in Fig. 6.13, module 6 is indeed the best case with a loss on the TBR of -0.175%. The NWL is the lowest with a value of 0.9 MW/m^2 (see Fig. 6.14).

The worst case, with a NWL of 1.35 MW/m^2 (see Fig. 6.14), is module 3 with a loss on the TBR of -0.349%. The interesting part is that the loss on the TBR of modules 3 and 4 is the same or, being more accurate, it is not significantly different.

The explanation for these results is the same shown in Chapter 6.2.3. The antenna is less absorber than the breeding blanket and therefore the flux behind the antenna is locally bigger when there is antenna, and thus the absorption is also bigger. This effect smoothes the impact of the antenna the more deep the blanket is. NWL in module 4 is 1.2 MW/m^2 and in module 3 is 1.35 MW/m^2. The difference is rather small and the breeding zone is long enough to smooth the difference into a no-significant difference.

To better understand this concept the neutron absorption in both cases should be studied. In case of placing the antenna in module 4 (Final Configuration), the absorption in different parts of module 4 can be seen in Tab. 6.18, and it should be compared to the absorption in different parts of module 3 when the antenna is placed in module 3 (Tab. 6.19).

	Without antenna	**With antenna**	**Variation (%)**
FW (W first layer)	4,016E-03 0.0017	3,501E-03 0.0018	-12,824%
Blanket breeder	1,829E-01 0.0008	1,777E-01 0.0008	-2,843%
Side walls	2,846E-03 0.0023	3,135E-03 0.0022	10,155%
FW (Steel second layer)	7,311E-03 0.0009	6,300E-03 0.0009	-13,833%
Straps (antenna)	-	2,405E-03 0.0017	-

Table 6.18 MCNP results for neutron absorption in different parts of module 4 when the antenna is placed in module 4 (Final Configuration)

	Without antenna	With antenna	Variation (%)
FW (W first layer)	4,159E-03 0.0017	3,618E-03 0.0018	-13,008%
Blanket breeder	1,953E-01 0.0008	1,902E-01 0.0008	-2,611%
Side walls	3,020E-03 0.0022	3,332E-03 0.0020	10,331%
FW (Steel second layer)	7,926E-03 0.0009	6,837E-03 0.0009	-13,740%
Straps (antenna)	-	2,534E-03 0.0016	-

Table 6.19 MCNP results for neutron absorption in different parts of module 3 when the antenna is placed in module 3

As seen before, NWL is bigger in module 3 (1.35 MW/m^2) than in module 4 (1.2 MW/m^2) and therefore all the neutron absorption values are bigger in the first case. However, if one check the variations, it can be seen that the differences are smaller. Actually the variation of the absorption in the breeding zone is bigger in module 4 (-2.790%) than in module 3 (-2.611%), because the more neutrons, the bigger the effect of getting the loss of TBR smoothed throughout the breeding zone. If the absolute variation is checked instead of the relative variation, the loss in case of module 4 is given in Eq. (1) and the loss in case of module 3 is given in Eq. (2), both extracted from Tab. 6.18 and Tab. 6.19.

$$1.828 * 10^{-1} - 1.777 * 10^{-1} = 0.0051 \qquad (1)$$

$$1.953 * 10^{-1} - 1.902 * 10^{-1} = 0.0051 \qquad (2)$$

The absolute difference is the same and that means that the blanket has smoothed the small NWL difference.

The most interesting conclusion of this section is that the loss on the TBR regarding the poloidal position will be always between -0.175% (best case) and -0.349% (worst case), and that even in the worst case the loss is really small. The poloidal position is especially interesting to study, not for its neutron effect like the antenna depth or the covering ratio, but for the flexibility that brings to the antenna itself. There are other heating auxiliary systems and diagnostic devices that may be placed in DEMO, and most of them require the equatorial or the upper port because there is an opening in the vacuum vessel behind them. The possibility of placing the antenna in another module allow the possibility to have the antenna as a complement of other systems and devices, and this could not be possible if the effect on the TBR would not be that small.

7. Budget

This project has been done in Germany by a student from Barcelona because of facilities requirements. It is very difficult to quantify the corresponding budget for one employee by the use of a Central Supercomputer in a research institute, as well as other kinds of software. Therefore, the budget will be done taking into account that the engineer is paid in Spain and the flight and the accommodation in Germany need to be included.

This project was presented in May 2015 in a conference in Lake Arrowhead, California. Also the flight to Los Angeles for the Conference, as well as the conference itself must be included.

Concept	Units	Unity cost (€/unit)	Cost (€)
Salary (annual)	0,75	21999,18	16499,39
Flights BCN - Germany	9	80	720
Flights BCN - LA	2	350	700
Conference in LA	1	839	839
Accommodation	9 (months)	475	4275
Total cost			23033,39
Tax (IVA, 21%)			4837,01
Final Cost			**27870,40**

Table 7.1 Summarize of the principal expenses for this project

The salary has been extracted from the salary tables established by C.C.O.O. for 2015 [CCOO, 2014].

The cost to make this project is 27870,40 €.

8. Environmental impact

The environmental impact of this work can be separated into two groups: during the realisation of the project and its consequence in the future.

As well as this project consist in simulations, there is not any other waste than the normal in an office. It is difficult to quantify the pollution produced for a big research institute with thousands of employees. Probably the biggest impact would be to travel from and to Germany by plane, which was done 9 times.

The environmental impact in the future is maybe even more difficult to predict. This work is done for DEMO, which is likely to be ready in the middle of the 21th century. It is obvious that fusion will represent a great advantage in environmental impact terms compared to almost any other source of energy, but it is impossible to quantify it right now.

Conclusions

The objective of this thesis was to quantify the loss of TBR for a distributed antenna in a DEMO reactor. This thesis was carried out in two different facilities in Germany, the Max Planck Institut für Plasmaphysik (IPP) in Garching and the Karlsruhe Institute of Technology (KIT) in Karlsruhe.

The first part, in IPP, consisted in gathering all the boundary conditions of the antenna and get a representative configuration of it. The second part, in KIT, was to perform Monte Carlo calculations in order to quantify the loss of TBR for the distributed antenna.

After implementing the antenna in a DEMO updated geometry and converting it to a MCNP geometry with the program McCad, the loss of TBR was calculated for the representative configuration of the antenna. Finally, a parametric analysis was done for five different parameters in order to still be able to predict the loss of TBR if some of these parameters are changed.

Using MCNP-5 for the simulations with the nuclear library FENDL-2.1, the loss of TBR for the final configuration is 0.35%, which has been proved to be very low. The final TBR is 1.14, which still has enough margin to ensure the tritium self-sufficiency for DEMO. The 67 m^2 of the antenna are, then, equivalent to a single port opening on the equatorial plane of 1.4 m^2.

The parametric analysis includes the type of breeding blanket, the covering ratio of the straps, the depth of the antenna, the thickness of the straps and the poloidal position of the antenna.

The best case regarding the type of breeding blanket, in the present design, is the HCPB concept of the final configuration (-0.35%), followed by the WCLL concept (-0.51%) and the worst case is the HCLL concept (-0.53%).

The covering ratio of 0.49 is the best case (-0.18%) and 0.94 is the worst (-0.44%), complementing the final configuration of 0.72 (-0.35%).

When doubling the depth of the antenna to 40 cm, the loss of TBR increases from -0.35% (20 cm of the final configuration) to -0.52%.

In terms of the thickness of the straps, the best case is the 2 cm of the final configuration (-0.35%) and the worst case when the thickness is 4 cm (-0.61%). In the middle there is the case of a thickness 0.2 cm tungsten plus 2.5 cm Eurofer (-0.44%).

Finally, from the modules available to place the antenna (modules 3, 4, 5 and 6), the best case is 6, the outboard upper module (-0.18%), and the worst is 3, the outboard equatorial module (-0.35%).

These very low results show that the tritium self-sufficiency will not be a problem in the development of the ICRF antenna if the configuration is not very strongly biased.

For the future work, all the effort should be concentrated in developing the antenna and after this process the TBR should be calculated again to have the final result.

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